**University of Alberta**

# Satellite Characterization of Vegetation Dynamics in the Western Canadian Boreal Plain

by

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# ABSTRACT

A total of 10 per-pixel Vegetation Phenological Metrics (VPMs) were developed to investigate the spatial and inter-annual phenological trends of 16 watersheds using 4 year time-series satellite Vegetation Index (VI) data. The VPMs, derived from the Enhanced Vegetation Index (EVI), coincided well with ground phenological observations and hence, were concluded to be realistic. The end of the growing season metric appeared to be a more sensitive indicator of the watershed health than the beginning; the longer growing season appeared to be a function of a delayed end rather than an early beginning, while industrial activities had a length shortening effect. Temperature is the major driver of the vegetation dynamics, especially in the wet years, with biomass accumulation being a function of Growing Degree Days (GDD) and moisture availability. The results, while initial, are encouraging and provide information about the physiological rather than the structural condition of the watersheds.

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# List of Abbreviations

| | |
|---|---|
| ANOVA | Analysis of Variance |
| AOI | Area of Interest |
| AOT | Aerosol optical thickness |
| ARMA | Auto Regressive Moving Average |
| ATBD | Algorithm Theoretical Basis Document |
| AVHRR | Advanced Very High Resolution Radiometer |
| AVI | Alberta Vegetation Inventory |
| AVIRIS | Airborne Visible/Infrared Imaging Spectrometer |
| AVIRIS | Airborne Visible/Infrared Imaging Spectrometer |
| BB | Blackbody |
| BIL | Binary Interleaved |
| BISE | Best Index Slope Extraction |
| BOREAS | Boreal Ecosystem-Atmosphere Study |
| BRDF | Bi-directional Reflectance Distribution Function |
| CV-MVC | Constrained View Maximum Value Composite |
| DC | Digital Count |
| DEM | Digital elevation model |
| DFMP | Detailed Forest Management Plan |
| DN | Digital Number |
| DTAC | Dark target-based atmospheric correction |
| EG | End of greenup |
| EOS | Earth Observing System |
| EOSDIS | Earth Observing System Data Information System |
| ESE | Earth System Enterprise |
| EVI | Enhanced Vegetation Index |
| fAPAR | fraction of absorbed photosynthetically active radiation |
| FMA | Forest Management Agreement |
| FMPM | Forest Management Planning Manual |
| FORWARD | Forest Watershed and Riparian Disturbance |
| ftp | File transfer protocol |
| GCP | Ground control point |
| GDD | Growing Degree Days |
| GIS | Geographic Information Systems |
| GMT | Greenwich Mean Time |
| HDF | Hierarchal Data Format |
| IMAR | Inner Mongolia Autonomous Region |
| L1B | Level 1B |
| L3 | Level 3 |
| LAI | leaf area index |
| Landsat | Land Satellite |

| | |
|---|---|
| LP DAAC | Land Processes Distributed Active Archive Center |
| LST | Land surface temperature |
| LULC | Land use land cover |
| MAS | MODIS Airborne Simulator |
| MAST | MODIS Administrative Support Team |
| MCST | MODIS Characterization Support Team |
| MCT | Multiple Comparison Test |
| MLST | MODIS Land Science Team |
| MODAPS | MODIS Data Processing System |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MODLAND | MODIS Land |
| MODLAND | MODIS Land |
| MQUALS | MODLAND Quick Airborne Looks |
| MS DOS | Microsoft Disk Operating System |
| MSS | Multispectral Scanning Spectrometer |
| MT | Mean Temperature |
| MVC | Maximum Value Composite |
| NASA | National Aeronautics and Space Administration |
| NBAR | Nadir bidirectional reflectance distribution function adjusted reflectance |
| NCEP | National Centers for Environmental Prediction |
| NDVI | Normalized Difference Vegetation Index |
| NIR | Near Infra Red |
| NOAA | National Oceanic and Atmospheric Administration |
| NPP | Net Primary Production |
| NRDC | National Resources Defense Council |
| OBC | On-Board Calibrator |
| OFRI | Ontario Forest Research Institute |
| OG | Onset of greenup |
| OGR | Operating ground rule |
| OGS | Onset of greenness/greenup and senescence |
| PGE | Product Generation Executive |
| PVL | Parameter Value Language |
| QA | Quality Assurance |
| REMAP | Regional Environmental Monitoring and Assessment Program |
| RMS | Root mean square |
| RS | Remotely sensed |
| SD | Solar Diffuser |
| SDSM | Solar Diffuser Stability Monitor |
| SRCA | Spectroradiometric Calibration Assembly |
| TM | Thematic Mapper |
| TOA | Top-of-atmosphere |
| TP | Total Precipitation |
| TR | Total Rain |
| TS | Total Snow |
| U.S. EPA | United States Environmental Protection Agency |

| | |
|---|---|
| USDA | United States Department of Agriculture |
| VI | Vegetation Index |
| VPM | Vegetation phenological metric |
| WQ | Water Quality |

# Chapter 1

# Introduction

## 1.1 Sustainable Forest Management

Forests cannot be managed wisely and efficiently in isolation without taking into account the larger landscape in which individual stands occur (Sachs et al. 1998). Considerable uncertainty exists, however, as to how natural and anthropogenic disturbances and management actions interact to determine landscape patterns and consequently how this interaction implicates sustainable resource management in terms of overall forest health preservation. Moreover, the current knowledge base falls short of predicting the effects of multiple land uses in catchment areas that overlap in time and space.

Poor forest management can have serious long-term consequences. For instance, management actions such as harvesting can alter landscape patterns (Franklin and Forman 1987; Ripple et al. 1991; Spies et al 1994) which in turn can impact biodiversity (Harris 1984, Lehmkuhl et al. 1991). Furthermore, management implications are crucial to water quality (Griffith 2002), regional climate and hydrology (Jones and Grant 1996), carbon budget (Dixon et al. 1994; Cohen et al. 1996), and global climate change (Schwartz 1999).

The above concerns have evolved into the conception of sustainable forest management, "the condition in which forest ecosystems sustain their complexity, diversity, resiliency, and productivity while providing for present and future human needs and values" (United States Department of Agriculture (USDA) Forest Service 2003). Sustainable resource management places considerable emphasis on maintaining forest ecosystem health, which is "the condition where a forest has the capacity across the landscape for renewal, for recovery from a wide range of disturbances, and for retention of its ecological resiliency, while meeting current and future human needs for desired level of values, uses, products and services" (USDA Forest Service 2004).

## 1.2 Background

The Canadian Boreal forests, like the Amazon forests, are of global importance to all living beings on earth. The thick layers of moss, soil and peat of the Boreal region are the world's largest terrestrial storehouse of organic carbon and play an important role in regulating global climate change (Natural Resources Defense Council (NRDC) 2002). Boreal forests comprise approximately 77% of the forested land in Canada and cover 60% of the land area in Alberta (Alberta Sustainable Resource Development 2001*a*).

In 2002, Canadian forestry export value was $42.9 billion, making Canada the world's largest forest product exporter with 18% of trade in international forest products (Natural Resources Canada 2003*a*). The industry employs 361,400 Canadians and acts as a backdrop for a tourism industry that is worth several billion dollars annually (Natural Resources Canada 2003*a*). Furthermore, in 2001, Canada produced 803 million barrels of oil and 6.5 trillion cubic feet of gas, making it the world's 14th largest oil producer and 3rd largest gas producer (Price and Bennett 2002). A report released by Greenpeace, ForestEthics and the NRDC show that since 1975, logging companies have cut 25 million hectares of Canadian Boreal forest; the amount of land clearcut has increased by 40% in the last 28 years, posing a significant threat to biodiversity conservation: 431 species are listed as at risk on Canada's federal endangered species' list in addition to those listed provincially (Greenpeace Canada 2003). Moreover, the oil and gas activities have led to 20% increase in greenhouse gas emissions from 612 to 726 million metric tones, from 1990 to 2000 (Price and Bennett 2002).

In Alberta, the scale of these industries is magnified; a major forestry trend is the intensification of harvesting practices (Natural Resources Canada 2003*b*). Forest harvest activities have increased in Alberta from 21.9 million $m^3$ in 2000 (Natural Resources Canada 2002) compared to 6.5 million $m^3$ in 1984 (McDougall 1986) with less than 9% of Alberta's Boreal forest left intact (NRDC 2002). In addition, Alberta is the home to most of the Canadian oil and gas supply that since 1990 have increased by 47% and 69%, respectively (Price and Bennett 2002). The energy industry harvests and accesses, on average, the same amount of land base as the forest industry (Smith et al. 2003*b*). While Alberta already has more than 150,000 kilometers of oil and gas roads slicing through the forest, to meet the growing demands, it is anticipated that 200,000 more gas wells would have to be drilled in Alberta, British Columbia, the Yukon, and the Northwest Territories within the next decade (Price and Bennett 2002).

The effects of this increased logging and oil and gas exploitation, as well as hydropower development, mining, road construction and other industrial activities in Alberta's Boreal ecosystem have led to a call from civil society for sustainable forest management practices. In order for industry and government to respond, tools are required that are verifiable and easy to use (Smith et al. 2003*b*) for the assessment and prediction of management impacts, to identify the biological and ecological system constraints for forest renewal, to investigate ecosystem response to stress, and to develop a clear picture of emerging and evolving problems in the wake of climate change issues.

**Figure 1-1:** Example of the Boreal plain landscape fragmentation in Swan Hills Alberta.

## 1.3 Alberta's Current Forest Management Infrastructure

Alberta's forest resources are managed through Forest Management Agreements (FMAs), which are area-based tenure agreement between a forest company and the Government of Alberta (Alberta Sustainable Resource Development 2004). It provides the forest company with the right to grow, harvest and remove timber (Alberta Sustainable Resource Development 2004). The terms of the FMA require forest product companies to assume full responsibility for the planning and sustainable management of forest resources within a designated area, and to produce a Detailed Forest Management Plan (DFMP) within every 10 years. FMA holders must use their own resources to obtain and distribute management and research information to stake holders including Government, quota holders, and the public. The DFMP reflects a company's strategy to manage timber on a long-term sustained yield basis and to effectively deal with forest health issues taking into account social, recreational, economic, biological and utilitarian aspects. The Government of Alberta prepares a Forest Management Planning Manual (FMPM) to direct how a DFMP within an FMA is to be written and approves the company's DFMP if it is written in accordance with the FMPM. The FMPM establishes the company's DFMP production schedule, lower level plan production and operating ground rules (OGR) construction (Smith et al. 2003*b*). Renewal of the FMA after 20 years is based on company performance and compliance with federal and provincial environmental regulation and policies (Alberta Sustainable Resource Development 2001*b*).

Smith et al. (2003*b*) and the Government of Alberta Sustainable Resource Development website at http://www3.gov.ab.ca/srd.html both provide a detailed insight into the interaction of the provincial government with forest product companies in managing the forested land base of Alberta.

## 1.4 Forest Watershed and Riparian Disturbance (FORWARD)

To date there is no formal process for integrating and assessing the cumulative impacts of industrial activities or other disparate overlapping human activities in Alberta's Boreal forests (Smith et al. 2003*b*). Recent provincial initiatives to develop policies and procedures to resolve these issues by moving from a focus on perpetual sustained yield to a holistic sustainable management approach have encouraged forest companies to operate within a fairly broad spectrum of management. Without comprehensive tools or sufficient base data to develop operating field procedures though, the need to monitor, model and research ecosystem dynamics has become indispensable. It was in this industrial context that the Forest Watershed and Riparian Disturbance (FORWARD) project was conceived.

Members of academia, industry, and regulatory agencies are working together in FORWARD to monitor 16 natural and disturbed test watersheds on the Western Boreal Plain ecozone of the Canadian Boreal forest in the Swan Hills of Alberta. FORWARD in particular is focused on determining the influence of wildfire and harvest disturbances on nutrient (phosphorus and nitrogen) release to fresh waters leading to marine pollution. Using state-of-the-art instrumentation, data on vegetation, soils, surface water quality and quantity, and bioindicators have been collected on treatment versus reference and before versus after disturbance on small watershed streams in order to generate the long-term database necessary to simulate distributed deterministic and probabilistic models. Model outcomes are to be linked into decision support tools, specifically Millar Western Forest Products' DFMP, and will be applied to planning and management practices (Smith et al. 2003*a*)

Building on previous sustainability initiatives in Alberta such as Terrestrial and Riparian Organisms, Lakes and Streams (TROLS), Sustainable Forest Management Network (SFMN) and Northern River Basins Study (NRBS) (Alberta Environment 2002), FORWARD offers linkages with other Canadian long-term small stream forested projects such as the University of British Columbia Malcolm Knapp Experimental Research Forest, Canadian Forest Service Turkey Lakes Watershed and the Legacy Experimental Forest.

Detailed background to FORWARD is published in nine peer-reviewed papers in a special issue of the Journal of Environmental Engineering and Science. The project website can also be accessed at http://forward.lakeheadu.ca.html.

## 1.5 Research Objectives

Management at the regional level requires data about large areas. Moreover, this data must be consistent and comprehensive enough to establish its statistical power of significance. Only remote sensing can provide such data over an entire area rather than providing a sampling of it, as would be the case with ground based measurements.

In addition, the detection and monitoring of major phenological transition dates are crucial to understanding the cumulative, large-scale effects of past and future forest management decisions. Many studies have shown that environmental factors are closely related to plant development and growth but the ability to predict environmental control of vegetation phenology remains inadequate. Surface-atmosphere interactions involve complex feedbacks (Moulin et al. 1997) since surface vegetation responds actively to climate variability. The vegetation response to climate variation requires a thorough understanding of vegetation phenological cycles and their relationship to temperature and precipitation (Zhang et al. 2004).

In this study, a suite of Vegetation Phenological Metrics (VPMs), using 4 year time-series satellite vegetation data, was developed to describe the phenological phenomena of 16 test watersheds in the FORWARD study area. The 4 year inter-annual variability of these metrics in 16 watersheds was also investigated to identify the most consistent phenological characteristics of these watersheds.

The main objectives of this research are to:

1. assess the validity of the Vegetation Phenological Metrics (VPMs);
2. characterize the temporal and spatial dynamics of vegetation in 16 FORWARD watersheds;
3. investigate the relationship between the vegetation phenological events and climatic conditions; and
4. assess the environmental control of vegetation phenology.

## 1.6 Research Questions

In order to fulfill these objectives, this study attempts to answer the following questions:

1. How do VPMs derived from Zhang method compare with those derived from Zhang modified method?
2. How do VPMs derived from Normalized Difference Vegetation Index (NDVI) compare with those derived from Enhanced Vegetation Index (EVI) in achieving above objectives?
3. Does high time-integrated Vegetation Index (VI) (biomass accumulation) correspond to the availability of more heat over the same year?

## 1.7 Research Approach

A forest manager's wish list includes answers to questions such as how large an area can be harvested at one time or with 2 or 5 years difference to achieve sustainable practices. What are the guidelines for road construction near a stream? what are the maximum disturbance levels for harvesting, regenerating and thinning a stand? what are the operating ground rules? how to do harvest allocation and determine the shape of a harvest plot? how does one develop spatial guidance patterns? what are the vegetation patterns to be developed in the course of time? what are sustainable management actions with respect to wildlife habitat, biodiversity conservation, water supply quality, climate change, air quality, soil preservation, ecological integrity and aquatic populations (Russell 2004, verbal communication)?

Ecosystem resource management implies a broad and fuzzy concept that has to be treated within the context of defined strategies, goals and objectives (More 1996). While this research does not attempt to provide an answer to each of these questions individually, it does adopt a holistic and interdisciplinary approach to develop tools that has the potential to deal with these issues at the ecosystem and watershed level of organization. Specifically, this research investigates the potential of satellite derived vegetation phenology as an effective indicator of sustainability and a reliable tool that can be applied to understand ecosystem functioning. Research conclusions may be useful in assessing ecosystem productivity at a regional scale (Duchemin et al. 1999), better accounting for forested ecosystems in modeling water and nutrient budgets, and quantifying the impact of climate variability on vegetation dynamics.

# Chapter 2

# Literature Review-I

Two areas of research are relevant to the research presented in this thesis: Remote sensing and the vegetation phenology. This chapter reports the literature dealing with the important aspects of remote sensing for assessing the vegetation condition. The review focuses on the remote sensing platform, and the theoretical background of vegetation indices used in this study. Concepts of image calibration, compositing, pre-processing, quality assurance and validation are also discussed.

## 2.1 Remote Sensing in Vegetation Studies

Remote sensing allows a scientist to gather information from a distance without coming into direct contact with the object or phenomenon of interest. While providing a systematic, synoptic view of the earth's cover over a wide range of spatial scales with repeated temporal sampling, it is a relatively cheap and easy-to-manipulate method of acquiring near-real time landscape data. Particularly, at larger scales, it is almost impossible to obtain consistent field observations to monitor vegetation conditions across different land covers which would represent ecosystem-level activity rather than species specific dynamics (White et al. 1997). In the last decade, various ecosystem models of evapotranspiration, photosynthesis and foliar nutrient cycling have been developed that require remotely sensed inputs such as Normalized Difference Vegetation Index (NDVI), leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (fAPAR).

### 2.1.1 The reflectance characteristics of vegetation

When sunlight strikes the earth's atmosphere and terrain features, each form of matter on earth transmits, absorbs, scatters or reflects solar radiation in a particular and characteristic manner. Chlorophyll in vegetation absorbs solar radiation primarily in the blue and red wavelengths to carry on photosynthetic activities, allowing green light to be transmitted through and reflected from the leaves. Leaf cell structure also scatters and strongly reflects non-visible near infra-red (NIR) radiation to avoid over-heating. This characteristic spectral response signature, as shown in Figure 2-1, can be used to distinguish plants from non-living features on the earth's surface provided that we measure the reflected sunlight from earth features. This was made possible with the advent of photographic (light-sensitive copper plates, photographic films) and non-photographic sensors (photodiodes, photoconductors and charged-coupled devices) sampling within narrow wave bands of electro-magnetic radiation (Norwood and Lansing 1983). Reflected long wave radiation measured by these remote sensing sensors manifests itself as digital numbers (DNs) in each pixel of an image and contains information about plant canopy structure and function. The recorded radiation then needs to be calibrated against reality, however.

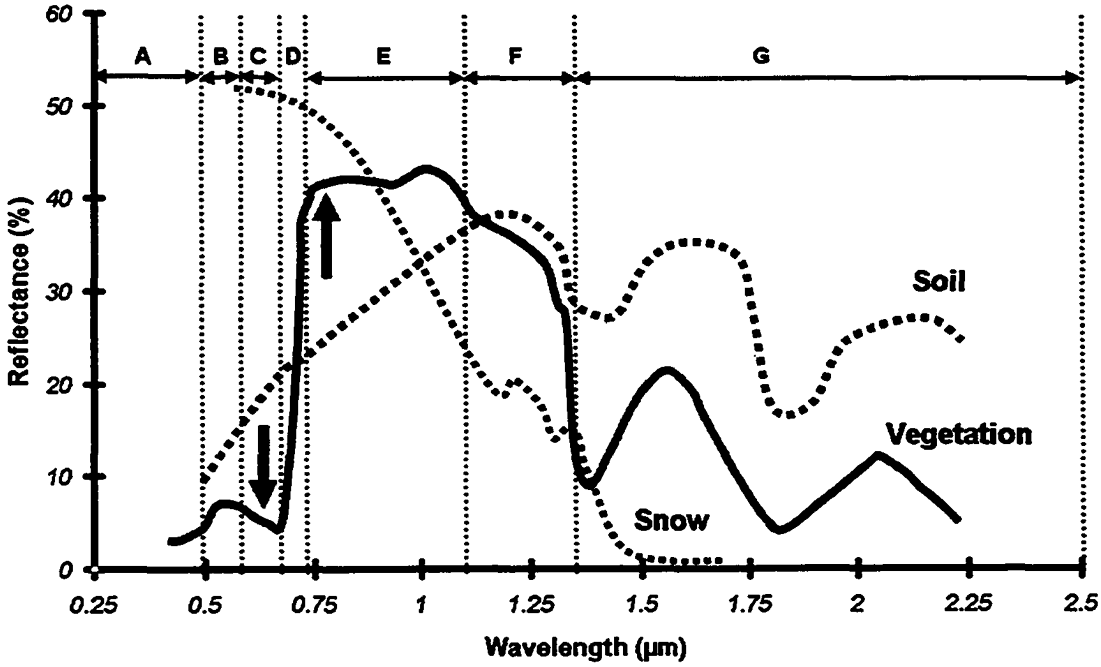


**Figure 2-1**: Spectral reflectance curve of a typical active vegetation with a generic soil and snow signature to show contrast. Region A: Chlorophyll blue light absorption, Region B: Green peak reflectance, Region C: Chlorophyll red light absorption, Region D: Transition, Region E: NIR plateau (strong reflectance): Region F: Transition, Region G: Leaf water absorption (developed from Tucker and Sellers 1986; Dozier and Frew 1981).

### 2.1.2 Vegetation Indices (VIs)

Vegetation Indices (VIs) are dimensionless, reflectance-based measurements computed from a combination of several spectral values that are added, divided or multiplied in a manner designed to yield a single value that indicates the amount or vigor of vegetation within the pixel. High values of VIs represent pixels covered by a significant proportion of healthy vegetation. VIs are used for their simplicity and relationship (either theoretical or empirical) to biophysical parameters (Asner et al. 2003). VI algorithms are designed to extract the vegetation signal portion from the measured reflected radiation by the sensor.

In general, VIs have been used to study watershed hydrologic processes, anthropogenic and climate change detection and modeling, agricultural activities (plant stress, insect attack, harvest yields), famine and drought early warning systems, landscape disturbances (volcanic, fire scars etc.), land use and land cover change, biophysical estimates of vegetation parameters (percent cover, fAPAR, LAI) and public health issues (Huete et al. 1999).

## 2.2 NASA's Earth Science Enterprise (ESE)

U.S. National Aeronautics and Space Administration (NASA) have several moderate and coarse spatial resolution sensing systems in orbit, scanning the whole earth's surface and collecting data. Earth Science Enterprise (ESE) is NASA's comprehensive program to study the earth as a complete environmental system. The overall objective of the ESE program is to determine how the earth is changing and the consequences for life on earth (Justice et al. 2002). Detailed background about the ESE program can be found at the NASA's website http://earth.nasa.gov/Introduction/index .html.

The Earth Observing System (EOS) is the key initiative of the ESE program. The EOS program, since its creation in 1958, has been focused on understanding the planet earth's air, land, water, and life as an integrated system, generating an extensive long-term database of remotely sensed observations. Key areas of study include clouds; water and energy cycles; oceans; chemistry of the atmosphere; land surface; water and ecosystem processes; glaciers and polar ice sheets; and the solid earth (NASA EOS

2004). EOS includes a series of satellites, a science component, and a data system which supports a coordinated series of polar-orbiting and low-inclination satellites (NASA EOS 2004).

### 2.2.1 Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS (or Moderate Resolution Imaging Spectroradiometer) is the key sensor on board NASA's Terra and Aqua satellites, which are part of the EOS satellite constellation, launched from Vandenberg Air Force Base, CA (MODIS Administrative Support Team (MAST) 2004). Terra was launched on December 18 1999 and began collecting data on February 24 2000. AQUA was launched on May 4 2002 and began collecting data on June 24 2002. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon (MAST 2004). Aqua's afternoon observations, combined with Terra's morning observations, provide important insight into the daily cycling of key environmental parameters such as precipitation and ocean circulation. Terra flies in formation with Landsat 7, which is another EOS satellite with a 30 m resolution sensor, providing a multi-scale sampling system for land surface monitoring (Justice et al. 1998).

MODIS' design is built on National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) and Landsat Thematic Mapper (TM) experience, to provide improved monitoring for land, ocean and atmospheric research. It has the highest number of spectral bands of any global coverage moderate resolution spectroradiometer. The land imaging component of this sensor has been upgraded by adding spectral bands in the middle and long-wave infrared (IR) and providing spatial resolution of 250 m and 500 m in addition to 1 km. The improved spectral resolution provides for better cloud and atmospheric characterization (Justice et al. 1998).

MODIS is viewing the entire earth's surface every 1 to 2 days, acquiring data in 36 spectral bands (MAST 2004). Table 2-1 provides technical specifications of MODIS sensor. Detailed specifications can be found at NASA's MODIS website http://modis.gsfc.nasa.gov/about/specs.html.

**Table 2-1:** MODIS' technical specifications (MAST 2004).

| Parameters | Specifications |
|---|---|
| Orbit | 705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua), sun-synchronous, near-polar, circular, inclination 98.2°, mean period 98.9 min, 16 day repeat cycle |
| Scan Rate | 20.3 rpm, cross track (Whisk broom) |
| Swath Dimensions | 2330 km (cross track) by 10 km (along track at nadir) |
| Field of view | 110° |
| Telescope | 177.8 mm diam. off-axis, afocal (collimated), with intermediate field stop |
| Size | 1.0 x 1.6 x 1.0 m |
| Weight | 228.7 kg |
| Power | 162.5 W (single orbit average) |
| Data Rate | 10.6 Mbps (peak daytime); 6.1 Mbps (orbital average) |
| Quantization | 12 bits |
| Daily coverage | 30° latitude |
| Spatial resolution | 250 m (bands 1 to 2), 500 m (bands 3 to 7), 1000 m (bands 8 to 36) |
| Design Life | 6 years |

### 2.2.2 MODIS Normalized Difference Vegetation Index (NDVI)

NDVI is a radiometric measure of vegetation that exploits the unique spectral signatures and behavior of canopy elements in the red and NIR portions of the spectrum (Asner et al. 2003). The two black arrows in Figure 2-1 indicate these unique spectral response regions. Deering (1978) came up with the normalized transform of the simple NIR to red reflectance ratio index, $X_{NIR} / X_{red}$ (Jordan 1969), designed to standardize VI values to between -1 and +1 (Huete et al. 1999). The equation takes the form:

$$\mathrm{NDVI} = \frac{\lambda_{NIR} - \lambda_{red}}{\lambda_{NIR} + \lambda_{red}} \qquad [1]$$

Where;

$\lambda$ = atmospherically corrected surface reflectances.

Rationing enables the NDVI to minimize calibration and instrument errors as well as changing reflectance conditions related to variable sun angles, cloud/shadow, aerosol content, atmospheric conditions and surface topography (Huete et al. 1999). High positive values of NDVI correspond to dense vegetation cover that is actively growing, where negative values are usually associated with bare soil, snow, clouds or non-vegetated surfaces.

NDVI derived from different sensors has been used by the research community in the last two decades and has been shown to correlate with several biophysical parameters such as chlorophyll density (Tucker et al. 1985), absorbed photosynthetically active radiation (Myneni and Williams 1994; Baret and Guyot 1991), LAI (Spanner et al. 1990; Asrar et al. 1984), productivity (Prince et al. 1995; Running 1990) and percent canopy cover (Yoder and Waring 1994). Relationships between fAPAR and NDVI have been shown to be near linear (Pinter 1993; Begué 1993; Wiegand et al. 1991). Other studies have shown the NDVI to be related to carbon-fixation (Raich and Schlesinger 1992; Fung et al. 1987), canopy resistance, and potential evapotranspiration (Running et al. 1989) allowing its use as input to models of biogeochemical cycles (Asrar et al. 1984).

MODIS NDVI is designed to serve as a "continuity index" to the existing NOAA-AVHRR 20-year global NDVI data set to provide for long-term vegetation monitoring studies. Huete et al. (1988) identified following disadvantages with the use of NDVI:

- an inherent non-linearity of ratio-based indices;
- the influence of additive noise effects (e.g. atmospheric path radiances);
- scaling problems;
- saturated signals over high biomass conditions; and
- sensitive to canopy background variations (strong NDVI degradation particularly, in higher canopy background brightness).

Because of NASA's EOS operational external noise removal, it was made possible to take advantage of non-ratio based indices (Huete et al. 2002) which are more linear with less saturation problems (Richardson and Wiegand 1977). This allowed for the introduction of alternative VIs for vegetation monitoring.

### 2.2.3 MODIS Enhanced Vegetation Index (EVI)

The EVI is MODIS-specific and provides improved sensitivity in high biomass regions. It was developed to enhance vegetation monitoring capability through a de-coupling of the canopy background signal and a reduction in atmospheric influences (Huete et al. 2002). It will, however, take time to be fully evaluated in terms of its applicability and limitations before being fully adopted by the researching community (Huete et al. 2002). In contrast to the NDVI algorithm, EVI utilizes the more atmosphere-sensitive blue band to correct the red band for aerosol influence (Kaufman and Tanre′ 1992). The equation takes the form:

$$\mathrm{EVI} = G\frac{\lambda_{NIR} - \lambda_{red}}{\lambda_{NIR} + C_1 \times \lambda_{red} - C_2 \times \lambda_{blue} + L} \qquad [2]$$

Where;

$\lambda$ = atmospherically corrected or partially atmospherically corrected (Rayleigh and ozone absorption) surface reflectances

L = canopy background adjustment (to correct for non-linear, differential NIR and red radiant transfer through a canopy)

C1, C2 = coefficients of the aerosol resistance term

G = gain factor.

Currently, the coefficients in the EVI algorithm are set to $L = 1$, $C_1 = 6$, $C_2 = 7.5$, and $G = 2.5$ (Huete et al. 1994; Huete et al. 1997).

The EVI algorithm makes use of a sophisticated compositing scheme which reduces angular, sun-canopy-sensor variations using the Constrained View Maximum Value Composite (CV-MVC) and with an option to use a Bi-directional Reflectance Distribution Function (BRDF) Model (Huete et al. 2002). Moreover, EVI is sensitive to canopy structural variations, including LAI, canopy type, plant physiognomy, and canopy architecture (Gao et al. 2000) whereas NDVI is more responsive to chlorophyll.

## 2.3 Remote Sensing Data Quality Considerations

MODIS VI data quality assessment includes calibration, image pre-processing, compositing, quality assurance (QA), and validation.

### 2.3.1 Calibration

Instrument calibration is the key to developing a stable time-series database. Pre-launch MODIS instrument characterization included radiometric, spectral, spatial, and polarization sensitivity analysis. On-Board Calibrators (OBCs); the Blackbody (BB), Solar Diffuser (SD), Solar Diffuser Stability Monitor (SDSM), and the Spectroradiometric Calibration Assembly (SRCA) generate various stimuli to monitor change in pre-launch characteristics and to establish post-launch absolute calibration in reflectance units in the reflective bands and in radiance units in the thermal bands (Guenther et al. 2002).

MODIS multiple calibration systems provide on-orbit calibration and ensure 2% calibration accuracy relative to the sun's radiance (Guenther et al. 2002). MODIS vicarious calibrations use high-altitude clouds and ocean observations to first perform the band to band registration and then the absolute calibration of the visible bands (Justice et al. 1998). Additional external calibration sources look at the moon and deep space. Looking at the moon provides for tracking degradation of the SD, while looking at deep space provides a photon input signal of zero, (stars are too dim to be "seen" by MODIS) which is used as an additional point of reference for calibration (MODIS Characterization Support Team (MCST) 2003). Detailed MODIS instrument geometry and calibration insight is provided by MCST (2003).

### 2.3.2 Image pre-processing

At-sensor recorded radiations from the terrain is a complex and composite function of the characteristics of the instrument; the size, shape, color, orientation, chemical composition and water content of plant, soils, water bodies; the density, distribution and juxtaposition of terrain features within landscape; and the noise introduced by the intervening atmosphere (Wilkie and Finn 1996). There is a history of VI research identifying limitations, which may impact upon VI utility in change detection, vegetation monitoring or biophysical parameter estimation studies. External influences and inherent variations to vegetation canopies (such as canopy structural effects associated with leaf angle distribution, clumping and non-photosynthetically active components) affect the VI values and hence must be accounted for before deriving any meaningful conclusions.

RS VI imagery artifacts can be introduced by many sometimes interrelated (overlapping), sources which include:

- sensor errors (gain, orbital drift);
- irregularities of detector response and scan mode (variations in mirror oscillations);
- incomplete transmission of instrument and ephemeris data from the satellite to ground stations (Roy et al. 2002);
- incomplete instrument characterization and calibration knowledge (Roy et al. 2002);
- geo-referencing and re-projection uncertainties (datum transformation, spheroid definition);
- satellite velocity and altitude variations (roll, pitch and yaw);
- effects of the earth's rotation, curvature and elevation;
- data corruption in production, archival and distribution;
- software coding bugs and configuration failures;
- algorithm sensitivity and robustness;
- variable sun illumination geometry with respect to sensor position; and
- spatial and temporal variations in smoke, gaseous and particulate pollutants, light cirrus clouds, clouds, shadows, aerosols content and water vapor.

Image pre-processing refers to the set of procedures or corrections applied to the raw at-sensor measured radiances (Level 0 product) to correct for most of the above-mentioned artifacts. These corrections are performed as "bulk" processing either at ground receiving stations or onboard the satellite systems. In the case of MODIS, MLST performs all necessary corrections to generate directly usable VI products.

#### *2.3.2.1 Atmospheric correction*

Multiple sources of radiances, other than that of the target (the target is the vegetation canopy in this study), exert an influence on the observed spectral response recorded by the radiometer. The atmosphere affects the radiance measured at any point in an image by attenuating the energy reflected from a ground object before it arrives at the satellite, and by acting as a reflector itself, adding a scattered, extraneous path radiance to the signal detected by the sensor (Lillesand and Keifer 1994). Scattered upwelling path radiance from the atmosphere increases red reflectance, while atmospheric scattering and water vapor absorption tends to lower the NIR signal. The net result is a drop in NDVI signal as a function of aerosol content and an underestimation of the surface vegetation.

The dark target-based atmospheric correction (DTAC) approach has been utilized in the MODIS surface reflectance product. The atmospheric algorithm is applied to cloud free pixels (using MOD 03 cloud mask product) with a solar zenith angle of less than 75°. It corrects for gaseous absorption, molecules and aerosol scattering, the adjacency effects, and the coupling effect between the atmospheric and surface BRDF (Vermote et al. 2002). Adjacency effects, caused by variation in land cover, refer to the measured top-of-atmosphere (TOA) radiances not only coming from the target but also from the adjacent pixels. The correction procedure currently relies on readily available ancillary data from National Centers for Environmental Prediction (NCEP) for the digital elevation model (DEM), surface pressure, ozone and water vapor content inputs (Vermote et al. 2002). It also relies on MODIS data itself for aerosol optical thickness (AOT), and water vapor (MOD 05) input. The algorithm uses pre-computed coupling factors and atmospheric scattering properties stored in tables (Vermote 2004). It also uses a simplified function to compute gaseous transmission and pre-defined land BRDF signatures for an atmosphere/BRDF coupling correction (Vermote and Vermeulen 1999).

Figure 2-2 gives an overview of the atmospheric correction procedure for the MODIS data. A full description of the atmospheric correction process is provided by the MODIS surface reflectance Algorithm Theoretical Basis Document (ATBD) (Vermote and Vermeulen 1999).

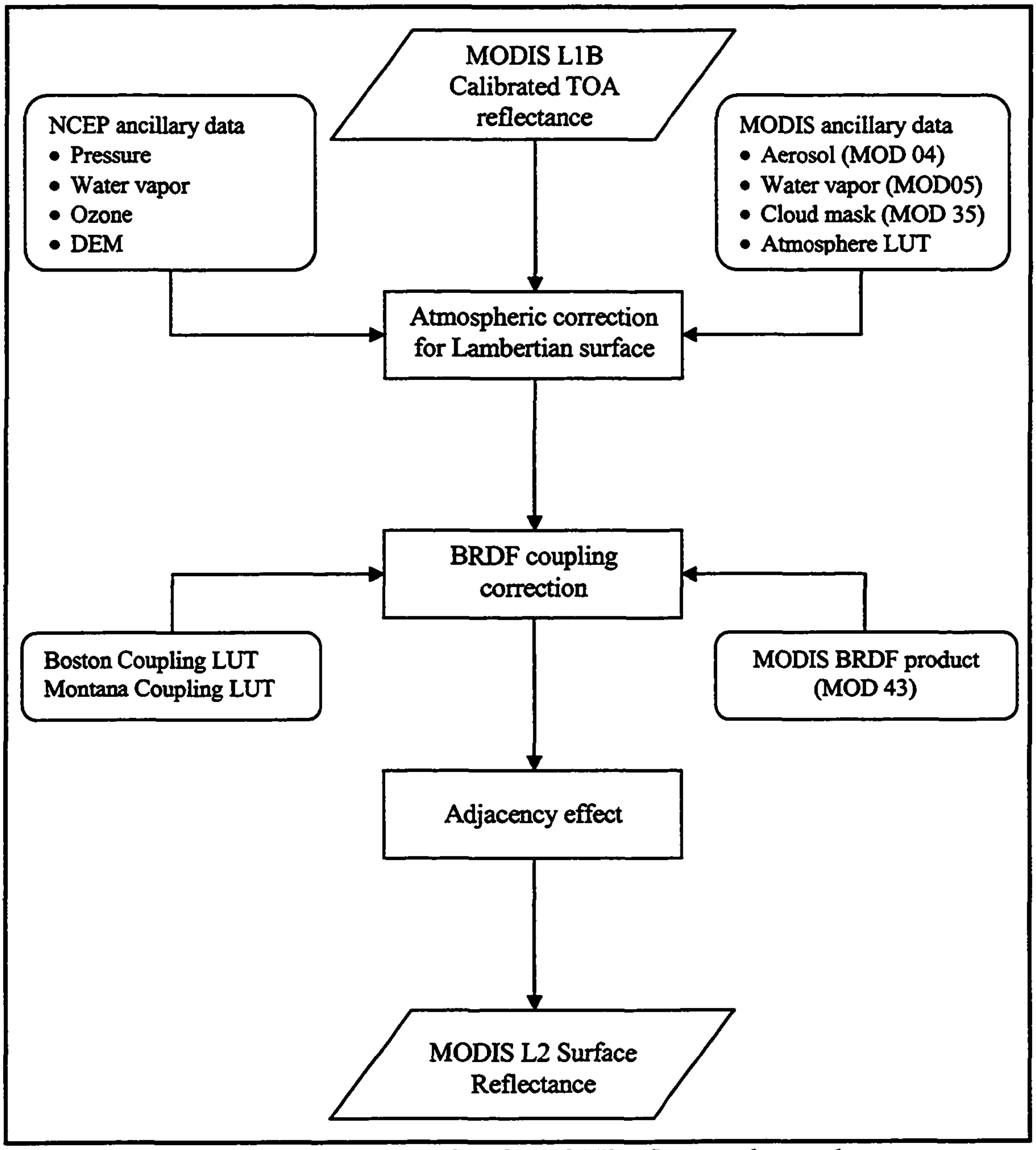


**Figure 2-2:** Atmospheric correction procedure for MODIS reflectance data product.

#### *2.3.2.2 Geometric correction*

Geometric correction addresses an image's spatial distortions introduced by the instrument sensing geometry, the curvature and rotation of the earth, surface relief, and perturbations in the motion of the sensor relative to the surface (Wolfe et al. 2002). The procedure first geolocates the sensed observations and then alters the data to correspond with true ground or image space in a known (or predefined) coordinate system.

MODIS geolocation is performed using a global network of ground control points (GCPs) to remove sensor orientation biases and trends (Wolfe et al. 2002). Exterior orientation (position and attitude) of Terra is measured in real time by sensors onboard the satellite, which enables geolocation of MODIS data to be approximately 150 m accurate at nadir. A global DEM (Logan 1999) is employed to model and remove relief distortion effects. The MODIS geolocation product is a Level 1 product and defines for each 1 km MODIS observation the geodetic latitude and longitude (WGS-84), terrain height, sensor zenith angle, sensor azimuth, slant range to the sensor, solar zenith angle and solar azimuth (Nishihama et al. 1997).

These geolocation data are also stored in the MODIS Level 1B (L1B) calibrated radiance products and in several MODIS Level 2 products as well as in the MODIS land L2G products (Wolfe et al. 1998). An estimate of the a priori root mean square (RMS) geolocation error is included in the metadata of every MODIS geolocation product. Nishihama et al. (1997) has provided detailed description about MODIS instrument geometry and geolocation algorithm.

### 2.3.3 Compositing

Although it is possible to collect data on a daily basis, it is rarely possible to consistently collect cloud-free data, especially over a large area. To overcome this problem, the composite imagery approach was developed. The compositing algorithm combines several images over a given time interval (16 days in this study) to create a single, cloud-free image with minimal atmospheric and sun-surface-sensor angular effects (Holben 1986), though the effects of translucent clouds and haze may not completely removed.

MODIS acquires the reflectance data from the earth's surface under varying solar illumination angles, sensor view angles, and atmospheric and cloud conditions. Variations such as off-nadir viewing and atmospheric aerosol content make direct comparisons between the radiance data difficult, and cause reductions in VI values (Holben and Fraser 1984). This situation led to the development of the technique called Maximum Value Compositing (MVC). The MVC algorithm selects the input pixel with highest VI value as output to the composited product. While it provides a solution, the disadvantage of using this approach is the unpredictable pixel selection due to anisotropic (or bi-directional reflectance) influences of the earth's surface. It selects off-nadir pixels with large forward-scatter view angles, large solar zenith angles (Figure 2-3), and with greater value than their nadir equivalent value (Huete et al. 2002), which may not be cloud free or atmosphere clear (Goward et al. 1991; Moody and Strahler 1994; Cihlar et al. 1994 1997). This limits the use of VI composite products for consistent and accurate comparisons. Figure 2-3 illustrates MODIS data acquisition and the sun-canopy-sensor angles.

In case of MODIS, atmospheric correction prior to compositing and VI computation has an impact of more pronounced surface anisotropy effects. Therefore, the MVC is anticipated to dramatically increase the selection of off-nadir pixels, particularly over open canopies (FORWARD study area has open canopy), which exhibit higher NDVI values when viewed obliquely (Huete et al. 2002). To compensate for this, constrained view maximum value compositing (CV-MVC) was introduced.

CV-MVC method selects the maximum value VI closest to the nadir-view. Another scheme, Bi-directional Reflectance Distribution Function (BRDF), utilizes all of the acceptable quality bi-directional reflectance observations to interpolate to their nadir-equivalent reflectance values from which the VI is computed and produced. Alternative compositing approaches are averaging VI values (Meyer et al. 1995) and The Best Index Slope Extraction (BISE) (Viovy et al. 1992). Cihlar et al. (1994) and Qi and Kerr (1997) have discussed few other VI compositing techniques.

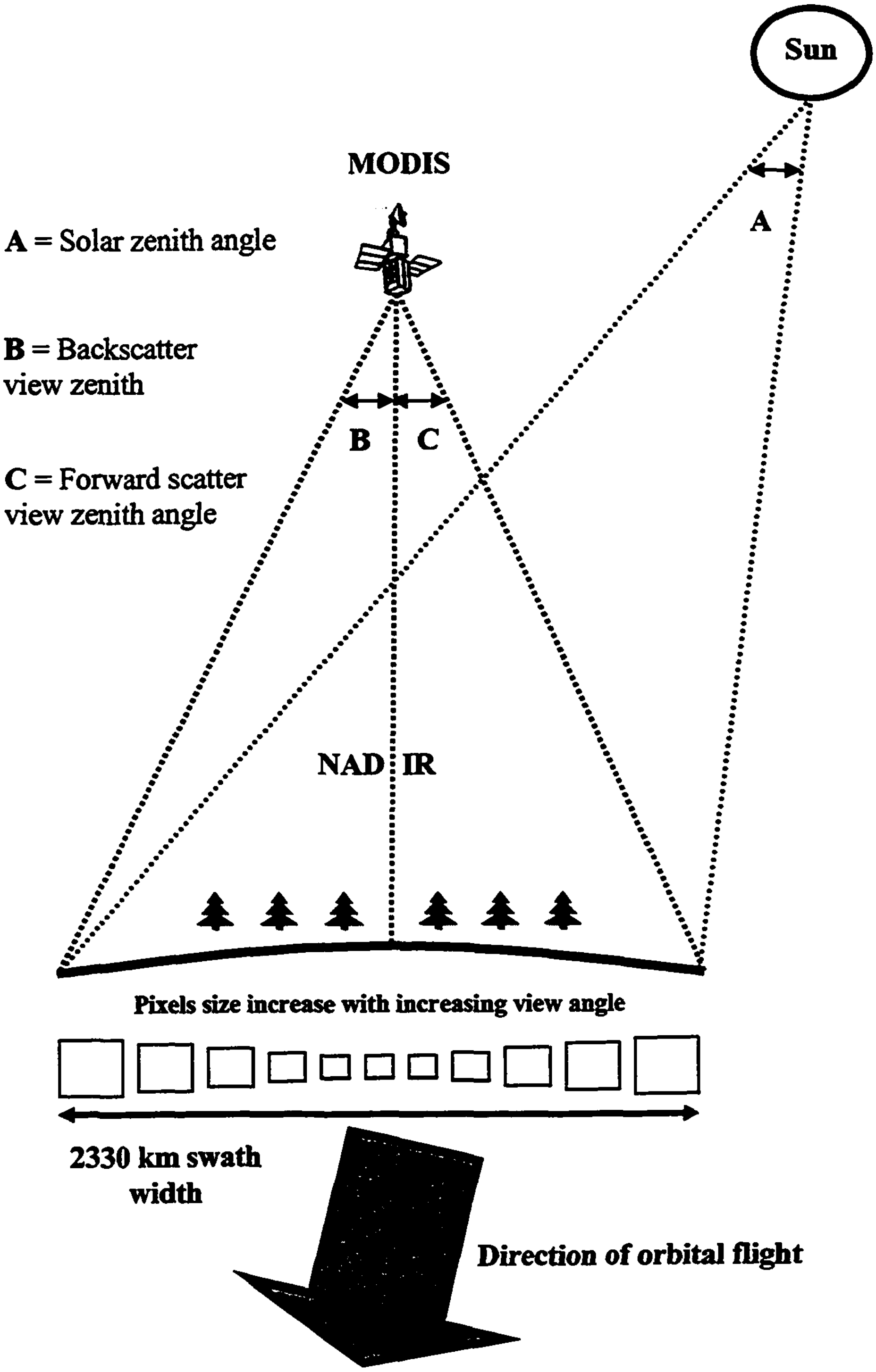


**Figure 2-3:** Illustration of MODIS data acquisition, sun-canopy-sensor angles, and increasing pixel size with the scan angle (developed from Huete et al. 1999).

### 2.3.4 Validation

The translation of radiometric VI's to biophysical, phenologic and change detection interpretations on the ground require validation efforts to assess error, uncertainty and performance. MODIS land products' validation is performed by analytical comparison of product samples with independently derived data from field based correlative measurements; output from canopy radiant transfer and bio-climatic models; experimental airborne measurements; and existing satellite data sets with established uncertainties (Justice et al. 1998). The goal is to provide a ground truth characterization of different land covers types to validate land products. For this purpose, the validation program leveraged and sought partnerships with existing sources such as science data networks and international research efforts. A summary of data sets used in MODIS VI validation is presented in Appendix A.

Measures of success for the accuracy and performance of VIs are assessed by conducting tests such as baseline, threshold and saturation VI value extraction, correlative measurements, seasonal profiles, transition zones, and in-situ nadir-based reflectance measurements over a global set of different validation sites. These validation or ground-truth sites are radiometrically and biophysically characterized and provide an infrastructure for the establishment of a semi-permanent array of EOS land validation, which includes a flux tower for long term time-series data collection of terrestrial biophysical dynamics (MODIS Land Team (MODLAND) 2004). Morisette et al. (2002) provides a description of the primary validation data sources and sites. Pre-launch validation efforts focused on testing the robustness of the algorithm with MODIS-like data sets (Huete et al. 1999) over a range of representative conditions. Data collected as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) (BOREAS Information System 2004) has been used for VI validation over FORWARD study area. The data included MODIS Airborne Simulator (MAS) (1994) and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (1996) overflights over the Boreal forest in growing and snow covered seasons; and field biophysical and radiometric (Parabola-SE-590) measurements with sun photometers. Post launch validation efforts include an airborne radiometric system for rapid and low cost land production validation called MODLAND Quick Airborne Looks (MQUALS). Detailed information about the MODIS land validation is provided by MODIS Land Team (2004), Morisette et al. (2002) and Huete et al. (1999).

### 2.3.5 Quality Assurance (QA)

Product performance information is required to consider the VI imagery in their appropriate scientific context. The MLST has developed detailed procedures to evaluate the VI data quality with respect to their intended (or anticipated) performance through quality assessment and validation activities. The scientific quality of data products is documented and stored in the MODIS VI file at the pixel level and as metadata at the product file level (Roy et al. 2002). These results are generated in the production algorithm and by post-production assessment (Roy et al. 2002) to help users to filter data that is unsuitable for their applications and to develop error estimates. Data products are re-processed several times because error may be introduced at any time during the instrument life and may not be identified for a considerable time (Land Data Operational Product Evaluation (LDOPE) 2002). Therefore, once QA has been performed, any product issues identified later are posted online on the Known Product Issues Website (LDOPE 2004). Product cases are categorized as "reopened", "closed", "note" or "pending" and are updated by LDOPE personnel to reflect current status (Roy et al. 2002).

#### *2.3.5.1 Pixel level quality*

The MODIS VI product includes two QA science data sets (SDSs) namely 250 m 16 days NDVI Quality and 250 m 16 days EVI Quality. These layers are raster images of the same dimensions and identical format as the NDVI and EVI data images. Each pixel consists of a 16 bits field that reflects conditions under which it was acquired and processed (Huete et al. 1999). Table B-1 and Figure B-1 in Appendix B lists the names of the bit-fields, numbers of bits assigned to each bit-field and the bit combinations and corresponding descriptions.

#### *2.3.5.2 File level quality*

VI product quality information is provided as metadata objects in the accompanying metadata file. These objects summarize tile-level data quality and are useful for ordering, screening and assessing purposes. Table B-4 in Appendix B provides the list of 18 metadata objects accompanying the MODIS VI product, characterized by five attributes namely object name, object type, group name, description and level. Table B-2 in Appendix B provides the relationship between the per-pixel QA bits and QA SDS metadata objects. Table B-3 in Appendix B presents the VI Usefulness Index scaling method. Detailed understanding of QA analysis, definition, scope and approach is provided by Huete et al. (1999), Roy et al. (2002), and MLST (2004).

# Chapter 3

# Literature Review-II

This chapter addresses the role of vegetation phenology in forested ecosystem monitoring. The review focuses on past remote sensing efforts to model vegetation seasonal changes, different methods employed to derive satellite phenological parameters, and time-series data quality considerations for phenological studies.

## 3.1 Phenology

Phenology is the study of the periodic biological occurrence of animal and plant phenomena in relation to the weather and climate. Daubenmire (1968) defined phenology as the relationship of the seasonal sequence of climatic factors to the timing of growth and reproductive phases in vegetation, such as the initiation of seasonal growth, time of blooming, time of seed set, and the development of new terminal buds. However, the U.S. International Biological Program Phenology Committee suggested a broader definition of phenology: "the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species" (Lieth 1974).

Phenological records have a history of more than 300 years in Europe and involved noting the first dates of such exciting observations as the flowering and budburst of native plants, the appearance of butterflies, the arrival of swallows, and hearing a cuckoo. In Canada, extensive phenological observations were initiated by the Royal Society of Canada in the 1890's. Alberta has phenological records of native species since 1973. Plantwatch, initiated in 1995, is a successor to Alberta's previous phenology initiative, Alberta Wildflower Survey, which started in 1987 and involved 200 volunteers reporting on three flowering stages for 15 native plants (Beaubien 2000). Plantwatch was expanded in 2001 by adding more plant species and establishing linkages to Environment Canada and the Canadian Nature Federation as well as involving representatives from all provinces (Beaubien 2000). Data tables and maps of budburst times are maintained by the University of Alberta Devonian Botanic Gardens and are updated regularly online (Beaubien 2004).

## 3.2 Phenology: Indicator of Stress and Measure of Ecosystem Resilience

The timing and progression of canopy development may help to infer the conditions of plants relative to their environment, including soil moisture, soil temperature, illumination, air temperature, weather and precipitation (Reed et al. 1994). Vegetation growth dynamically responds and adapts to prevailing environmental conditions. The dynamics are manifested as changes in the distribution of vegetation types, plant growth and development (Belward 1991). Liebig's law of minimum states that "plant growth is limited by a single resource at any one time; only after that resource is increased to the point of sufficiency can another resource enhance plant growth". However, if plants compensate for resource imbalance in the environment, growth should be equally limited by all resources (Bloom et al. 1985). Factors such as seasonal reductions in temperature, mild frosts, photoperiodic effect of reduced seasonal day length mediated by phytochrome, drought, flooding and nutrient deficiency, increase rate of leaf senescence. On the other hand, high nitrogen levels and high concentrations of zinc, iron, chlorine, and iodine decrease the rate of senescence (Ontario Forest Research Institute (OFRI) 1997). If younger foliage in an evergreen tree exhibits early senescence, it is likely that the tree is suffering from fairly large imbalances of nutrients or some other stress (OFRI 1997). Similarly, changes in soil fertility, site quality, forest succession, and species composition in relation to abiotic and biotic disturbances such as severe climatic conditions, fire, pathogenic organisms including insects and diseases, foraging animals and competing vegetation significantly affect the growth and hence alter the phenological transition dates of canopy growth (Weetman 1983). Moreover, stresses such as air pollutants, ozone, herbicides, pesticides and fertilizers and intentional intervention such as harvesting or the implementation of silviculture practices, reforestation, protection or conservation programs etc. may have positive or negative impacts on plant growth.

Reed et al (1994) reported that temperature, photoperiod and moisture play a vital role in the photosynthetic activity of the deciduous and coniferous forested landscape with specific adaptations of different species. Nienstaedt (1974), too, demonstrated that temperature plays a major role in the control of phenological response of North American tree species. Particularly in the Boreal region, the start of the vegetation growth period is usually related to temperature (Cannell and Smith 1986) because the ecosystem is limited by radiation rather than by moisture. Evapotranspiration increases with increasing temperatures causing excess water loss which can severely stress trees. Consequently photosynthesis may decline or level off. Changes in photosynthetic rates influence carbon and nutrient assimilation and water use which act to re-allocate resources towards maintaining vigor, growth, reproduction and defense functions (Browning 1995; Cannell and Jackson 1985; Ross and Pharis 1985; Stephenson 1981). In temperate zones of the earth, timing of spring growth phases, for example, budding, leafing, and flowering of plants, is primarily a response to accumulated temperature above a threshold value (Beaubien and Freeland 2000). Short days also induce dormancy in woody plants (Vegis 1964; Nooden and Weber 1978). With critical day length being a function of latitude, northern populations become dormant while southern species continue to grow for the same day length (Oleksyn et al. 1992).

Changes in phenological events may therefore be indicative of important year-to-year climatic variations and even global environmental change (Reed et al. 1994). In Canada, a linear trend increase of 0.8 °C in summer (Environment Canada 2004*a*) and 1.2 °C in spring (Environment Canada 2004*b*) temperatures from 1948 to 2004 have been observed. Specifically in western Canada, summer and spring warming of 0.9 °C to 1.7 °C has been observed over the last century (Gullet and Skinner 1992), as opposed to parts of eastern Canada. Plantwatch flowering data also reflects this change, with timing of first bloom (10% pollen shed) of Aspen poplar (*Populus tremuloides*) in Edmonton, Alberta now occurring almost a month earlier than it did a century ago (Beaubien 2000). Beaubien (2000) reported El Nino as one of the factors causing the earlier bloom times. Moreover, January temperatures are rapidly warming in the Canadian Prairie Provinces (Chapman and Walsh 1993). It is anticipated that the climate warming will disrupt the local adaptation of plants to a combination of thermal and photoperiod regimes since it contributes only to heat accumulated and doesn't affect photoperiod at all (Lechowitz 1995).

The above literature suggests that because vegetation phenology is responsive to both climate and human disturbances, it may serve as a good indicator of ecosystem health and as a means to measure cumulative stress in an ecosystem. In addition, it integrates and reflects the response of the earth's biosphere to inter- and intra- annual climate dynamics and hydrologic regimes (Myneni et al. 1997). Therefore, phenological information has the potential to provide us with a measure of ecosystem resilience. It is for these reasons that vegetation phenology is considered as core variable for the monitoring of environmental change by Environment Canada's Ecological Monitoring and Assessment Network (EMAN) (EMAN 2003), established in 1994.

## 3.3 Remote Sensing and Phenology

Until recently, most work on phenology studies has been limited to individual animal or plant species. With the advent of high temporal global satellite imagery, data is now available to examine and monitor biome and ecosystem level phenological event changes. This has led to a new interdisciplinary science of landscape ecology. Vegetation phenology/dynamics monitoring on both regional and global scales is concerned with community, biome and ecosystem levels of organization. A single satellite observation in time, then, is of limited use in successfully characterizing the ecosystem dynamics and classifying vegetation except in areas of low dynamic activity (change in density, color, or canopy architecture of a vegetation canopy that manifests itself as changes in chlorophyll and other light absorbing pigments discernible by satellite sensors).

### 3.3.1 Satellite versus ground based phenology observations

Satellite derived phenology is fundamentally different from traditional ground based observations. The phenological response to environmental variables varies according to the species and location factors such as elevation and aspect of the plant community. Satellite sensors have not yet achieved high enough spatial resolution in conjunction with the high temporal resolution to detect such phenological events of individual species as leafing, budding and flowering, though, these sensors are still capable of measuring broad scale changes in the landscape that are indicative of ecological health. Satellite detection of phenological stages is a subjective process (White et al. 1997). It is very difficult to objectively define an absolute start and end of a growing season (onset of greenup and senescence (OGS)) from satellite observations (White et al. 1997). The strict definition of greenup onset depends on the objectives of a study but they roughly point towards the same concept as of budburst, flowering and blooming used in ground-based phenological studies. However, OGS avoid connection to the field phenology measurements and imply the concept of satellite based phenology. Satellite based phenology accounts for pixel level activity rather than species specific activity. Each pixel represents the composite response of several vegetation communities (possibly mixed with non-vegetated surfaces e.g. water bodies) sampled over an area equal to the spatial resolution of the imagery (in this case 250 m x 250 m). Overall, linkage between these two types of phenological information yields a better understanding of how climate induced individual species-level responses aggregate to larger scales (Zhang et al. 2004).

### 3.3.2 RS phenological research review

Phenology is highly variable (Schmidt and Lotan 1980) and responds to long term variation in climate (Sparks and Carey 1995). Phenological signals can be influenced by various local and genetic factors, permitting plants to serve as a reliable indicator of environmental change (Schwartz 1997), especially temperature variations in the spring season (Myneni et al. 1997; Schwartz 1999). Therefore spring plant phenology data is extremely useful in monitoring climatic variation.

A number of studies focusing on the analysis of global and continental-scale vegetation patterns using NOAA AVHRR data were initiated in the mid 1980s. For example, Goward et al. (1987) studied selected biomes in North and South America and observed that temporal variations of similar vegetation types were correlated to known climatology of the continents; in 1990 Lloyd employed phenological classification of global vegetation cover in which classes were defined in terms of timings, duration and intensity of photosynthetic activity derived from multi date AVHRR NDVI data using a supervised binary decision tree.

Reed et al. (1994) computed twelve key Vegetation Phenological Metrics (VPMs) using NDVI 1 km data derived from NOAA AVHRR sensor. Data was collected from 1989 to 1992 over conterminous United States (U.S.) and a strong coincidence was observed between satellite derived phenological metrics and expected phenological characteristics of known land cover types. In particular, these metrics were successful in characterizing the phenology of four types of grasslands and spring wheat in North Dakota, and differentiating between coniferous and deciduous forest stands. These results validated the significance of VPMs and portrayed these as potential tools for monitoring global environmental change. They further postulated that an increase in variability of deviation of VPMs in a region may be a signal to conduct more detailed land cover assessment with high resolution imagery and ground truthing. The authors mentioned that some metrics have more applicability for selected land cover types and may have shortcomings for others. For example, the time integrated NDVI metric was identified to have shortcomings in coniferous dominated regions whereas rate of greenup and senescence effectively discriminates between deciduous and coniferous stands.

In another study Reed and Schwartz (1999) used AVHRR NDVI 1 km data for the period 1990-1995 over conterminous U.S. to report correlations between satellite derived phenology and ground-based modeled phenological outputs. First leaf and first bloom dates were found to be positively correlated with sensor detected onset of greenness dates. Correlations were strongest for deciduous forests ($r = 0.62$) and mixed woodlands ($r = 0.64$), intermediate for tall grass ($r = 0.46$) and lowest for short grass ($r = 0.37$). However, a consistent earlier onset of greenup dates were detected by the AVHRR sensor when compared to modeled first bloom date across all land cover types. This finding led authors to suggest that AVHRR detects understorey greenup in the forest rather than overstorey species greenup. The low bi-weekly temporal resolution of satellite data and the relatively invariant climate of the years between 1991 and 1995 were identified as utility limiting factors of the analysis. For example onset dates in four out of five years in the Harvard forest site were all registered in the same bi-week thus making annual variability among most sites undetectable by the sensor.

Senay and Elliot (2000) characterized the spatial and temporal dynamics of Oklahoma vegetation using AVHRR bi-weekly NDVI data from 1990-1996 over the conterminous U.S. The authors identified dates and relative magnitudes for onset of greenness as well as peak and senescence for four land cover types, and reported a high inter-annual variability in the peak date and magnitude among the land cover classes compared to almost none for onset and senescence metrics. Moreover, they concluded that AVHRR NDVI was successful in discriminating rangelands with different canopy densities consistently across the years.

Roerink et al. (2003) quantified the impact of climate variability on vegetation dynamics using AVHRR NDVI 1 km data over part of Sahelian Africa and Europe and found that for dry areas, both the total amount of vegetation and the seasonal difference between dry and wet season increase with increasing precipitation. However, for wetter regions, the seasonal difference remains almost constant. Based on these observations, authors concluded that in wetter regions both precipitation and net radiation are the limiting factors for the vegetation growth.

Duchemin et al. (1999) used AVHRR NDVI 1 km data from 1989-1994 over deciduous forest located in France to monitor the OGS on three species. They found a good correlation between the satellite-derived budburst and budburst timing predicted from air temperatures using the thermal time model.

Lee et al. (2002) used AVHRR NDVI 1 km data from 1981-1991 over Inner Mongolia Autonomous Region (IMAR) to evaluate the relationships between vegetation phenological patterns and climatic variation. They built on the work done by Myneni et al. (1997) who used the same data from the same time period over northern hemisphere vegetation located between 45° N and 70° N latitude to asses the impact of climatic trends on vegetation. Onset of greenup was found to have advanced by 7 to 10 days from 1981-1991. They argued that earlier onset of greenup was associated with increased spring temperatures and earlier uptake of atmospheric $CO_2$. Lee et al. (2002) investigated vegetation phenological changes at lower latitudes such as IMAR located between 39° N and 49° N latitude. Little or no change in the date of onset of greenup was observed over forested and cultivated landscapes. Monthly mean temperature and precipitation measurements were claimed to successfully explain the difference in onset of greenup patterns.

Griffith et al. (2002) used AVHRR NDVI 1 km data for the year 1995 over Nebraska, Missouri and Kansas to seek interrelationships between VPMs and selected

Water Quality (WQ) variables which included conductivity, turbidity, total phosphorus, and nitrate-nitrite nitrogen. 290 stream sites were randomly selected in Kansas, Nebraska and Missouri and were sampled once by the U.S. Environmental Protection Agency (EPA) Region VII during the late spring and summer of 1994 and 1995 as part of its Regional Environmental Monitoring and Assessment Program (REMAP). VPMs were derived from time series NDVI data using algorithms modified from Reed et al. (1994). Spring NDVI values, mean date of onset of greenness and standard deviation of NDVI values at the onset of greenness were found to have the greatest number of significant correlations (r values up to 0.8) with stream WQ parameters. Peak NDVI date and magnitude were found to be frequently correlated with Index of Biotic Integrity and Habitat Index. Authors reported the potential for estimating summer WQ conditions using spring AVHRR NDVI data and supported Jones et al. (1997), who found that change in NDVI values over a 15 year period over U.S. Mid-Atlantic States was useful in assessing the watershed's relative vulnerability to conditions that affect stream water quality. They further built on land use/land cover (LULC) and water quality relationship studies (such as Omernik 1976; Osborne and Wiley 1988; Lenat and Crawford 1994; Roth et al. 1996; Allan et al. 1997; Johnson et al. 1997; Basnyat et al. 1999) and found that VPMs are more highly correlated to the WQ than were the LULC proportions. They argued that studies relating LULC to WQ employed traditional temporally static land cover maps and does not account for phenological, inter-annual or successional (human induced) changes. They pointed out that watershed boundary delineation, positional accuracy of the sampling point and general digitizing artifacts can introduce significant errors in the results. A major weakness identified with this study was potentially unreliable WQ data, since each stream was sampled only once. And, in some cases the year of water sampling did not even match the year of NDVI data acquisition. Despite these weaknesses, this research was claimed to be the first demonstration of empirical NDVI-stream WQ relationships on a regional, multi-state scale.

Zhang et al. (2004) used MODIS EVI 1 km data for the period from January 1 to December 31, 2001 to identify vegetation phenological transition dates and link these to MODIS land surface temperature (LST) data from the northern hemisphere between 35°N and 70°N. The onset of greenup was found to be 4 to 9 days earlier and onset of dormancy 2 to 16 days later for urban areas compared to adjacent natural forests. Authors reported that urban heat island effect, which results in 1 to 3 °C higher mean annual temperature in urban relative to rural areas, caused the difference. The growing-season length for forests was found strongly correlated with variation in mean annual LST.

The above studies indicate that time-series VI data are very useful for surveying vegetation status and that meaningful conclusion can be derived regarding the ecological conditions of the landscape.

## 3.4 Methods Used to Detect Phenology from Satellite Data

During the last decade a number of different methods have been adopted by researchers to characterize the seasonality of time-series VI data and to identify the timing of OGS and other derived metrics. These methods had considerable associated problems in identifying phenological key stages and have evolved since then.

### 3.4.1 Specific NDVI thresholds

This method uses a specific NDVI threshold value applicable across land covers at which the vegetation activity is assumed to begin: for example Fischer (1994) used 0.17, Markon et al. (1995) used 0.09 and White et al. (1997) used 0.5 NDVI threshold value to extract onset of greenness. Lloyd (1990) used 0.099 as threshold NDVI value which was the maximum value reported for Kenyan bushland in the period immediately before the growing season (Justice et al. 1986). The author points out that this threshold value needs testing in order to be applicable to a range of ecological zones. The constant threshold value is also species specific and varies with soil background and illumination conditions (Reed et al. 1994). Therefore it is not possible to establish a single meaningful NDVI threshold value for different land cover types at which vegetation activity is assumed to begin on the landscape.

### 3.4.2 Backward looking moving averages

This method adopted from Auto Regressive Moving Average (ARMA) models (Hoff 1983; Granger 1989) uses a comparison to a moving average of the time-series to identify departures from an established trend (Reed et al. 1994). This approach identifies the point where NDVI exhibits a sudden increase which is assumed to be the start of photosynthetic activity, though, measuring the beginning of the greatest increase in

NDVI during the start of the year may not correspond to the actual onset of greenness in case where land is covered by snow (Reed et al. 1994). A satellite sensor would signal the snow melt event as the greatest increase in NDVI which, in reality, is not onset of greenness. The authors also identified the potential problems with the running median method employed as a data smoothing technique. This method served well at minimizing the effects of extremely low NDVI values that were related to cloud contamination, but had the undesirable effect of presumed valid NDVI peaks. Reed and Schwartz (1999) updated the technique by incorporating an upwardly biased smoother to take advantage of "clean" high NDVI values, while smoothing lower values. Reed et al. (1994) have discussed this method in detail.

### 3.4.3 Largest NDVI increase

Kaduk and Heinmann (1996) used the largest increase in the NDVI time-series data, after the monthly mean temperature had reached 5°C, as an indication of budburst. The point corresponds to the onset of greenup. This method has the same problem of misinterpreting the snow melt event as 'largest NDVI increase' and is not applicable to land covered with snow at the start of the growing season.

### 3.4.4 Empirical equations

Moulin et al. (1997) used empirical equations to derive the start, the peak, the end and the length of vegetation cycle using AVHRR NDVI 1 km dataset for the year 1986. These equations included terms accounting for mean (mean NDVI term) and shape (derivative term) of NDVI signal. A soil threshold and a slope coefficient used in the algorithm were empirically set. A detailed description of the equations and considerations involved can be found in the Moulin et al. (1997). The authors reported that for the Boreal regions the detected onset of greenup corresponded to the date of snow melt. This observation can be linked to the findings of the Reed and Schwartz (1999) who attributed the under storey detection of the satellite sensor to the NDVI algorithm and not to the onset of greenup detection method employed.

### 3.4.5 Zhang method

Zhang et al. (2003) method used piecewise logistic functions, which are fit to remotely sensed VI data. Onset and dormancy transition dates corresponded to the time at which rate of change in curvature in the VI data exhibited local maxima or minima. This approach builds on the approach used by Badhwar (1980, 1984), who fit exponential and logistic smooth functions of time to extract the spectral reflectance variation for corn and soybean crops during growth stages. Authors claimed that this approach is well suited for global application and ecosystems characterized by multiple growth cycles within a single growth season (common for croplands and semi-arid regions). It also provides vegetation phenology monitoring in near real time and does not require pre-smoothing of the VI data or the use of a threshold VI value. A detailed description of the method is presented in Zhang et al. (2003).

### 3.4.6 Zhang modified method

The original Zhang's method relies on determining only the extreme point (maxima or minima) in the curvature rate of change of the function using the formula given by Zhang et al. (2003). This method was modified in a way that the point of maximum second derivative of the best-fit logistic function was also determined. The second point tended to occur a bit later than Zhang's point. Onset of greenup date was then determined by averaging the two dates obtained from the two points (Yu et al. 2004). The averaging had an effect of producing a smoother map, which was desirable.

## 3.5 Time Series Data Quality Considerations for Satellite Phenological Studies

The correct interpretation and meaningful extraction of conclusions from long-term time series of RS data requires the ability to discriminate between product artifacts and changes in the earth processes being monitored (Roy et al. 2002). For results to be comparable over time and location, time-series VI values should contain no spatial pattern that can be attributed to the random and systematic error in the data, though quantifiable spatially dependent systematic and random error may be present.

Previous RS phenology studies employed Landsat Multi Spectral Scanner (MSS) (79 m) and Landsat Thematic Mapper (TM) (30 m) sensors. For example, Odenweller and Johnson (1984) compared Landsat MSS time-series data to the expected phenological characteristics of different crop types to perform crop classification. Issues such as a 16 day repeat cycle, which represents too large a time step in the data to reliably assess VPMs, and cloud and haze contamination restricted the ability of these sensors to track key phenological events. The problem was solved by the launch of a high temporal resolution AVHRR sensor that collected data every day. Moreover, scientists came up with AVHRR data compositing approach to remove the cloud contaminated pixels from the imagery but calibration errors, poor geometric registration, cloud screening difficulties, less sophisticated compositing algorithms and the presence of off-nadir distorted pixels made AVHRR NDVI data not an optimum choice for vegetation monitoring applications (Goward et al. 1991). AVHRR was never designed for land applications and the operational VI products are based on the current needs for weather forecasting (Justice et al. 2002). Kasischke and French (1997) used AVHRR NDVI 1 km from 1990-1992 over Alaska and reported the critical constraints on the use of AVHRR data to map and monitor changes in vegetation for the Boreal landscape. These constraints included the effects of cloud and atmospheric haze, fire on forest succession, and forest stand patch size with respect to system resolution. Heterogeneous patches of forests smaller than the cell size of the AVHRR sensor in the study area would result in significant sub-pixel mixing (Kasischke and French 1997). Authors regarded Landsat TM spectral bands as superior to that of AVHRR for land cover applications. In addition to that, studies have shown that AVHRR instrument calibration has changed significantly following launch and drifted subsequently over time, which introduces the inter-annual variability in VI data unrelated to vegetation biophysical dynamics (Che and Price 1992; Kaufman and Holben 1993; Rao 1993; Teillet et al. 1990).

These artifacts make the AVHRR data not well suited for time-series vegetation phenology studies where induced data trend will be the result of faulty sensor calibration and cloud effects rather than the parameters under focus i.e. phenology and inter-annual weather changes.

### 3.5.1 Why use MODIS VI data

The growing need to precisely characterize vegetation dynamics led to the launch of a new earth observation satellite sensor MODIS that has higher spatial and spectral resolution. The MODIS EVI product provided the land research community with the flexibility to move beyond its dependence on the NDVI. The land bands have a heritage from the Landsat TM, with capabilities added in short-wave and long-wave infrared (Justice et al. 1998). MODIS data is well suited for the regular monitoring of forested ecosystems because:

- it is cost effective (currently the distribution of MODIS data is free of any cost);
- a large amount of effort has been put into the development of directly usable products i.e. the MODIS Land Science Team (MLST) is funded by NASA to develop the science algorithms and processing software used to generate an extensive set of land vegetation products such as NDVI, EVI, LAI, fAPAR etc. (Roy et al. 2002);
- MODIS land products quality is ensured by calibration, Quality Assurance (QA), and validation activities, which form an integral part of the MODIS land production chain;
- the seven "land" bands (from band 1 to 7) in MODIS are carefully chosen to minimize the impact of atmospheric gases' (particularly water vapor) absorption (Vermote et al. 1997) since canopy spectral signature is not only different at the ground level (no atmosphere) compared to satellite sensor level, but also varies temporally from image to image because the atmosphere and climate change with time;
- the atmospheric correction of MODIS provides a systematic aerosol correction at 1 km (Vermote et al. 2002), constituting a considerable advance on AVHRR Pathfinder dataset, which only relied on operational Rayleigh (standard atmosphere with zero or constant aerosol loading) and ozone effects correction;
- MODIS multiple OBCs for the calibration of the solar reflective regions accomplish a higher precision calibration. Additionally, they are periodically validated through vicarious calibration techniques for detection and correction of drift in calibration gains over time (Barbieri et al. 1997);
- knowledge of sun-canopy-sensor geometry is embedded as imagery in the MODIS VI data since MODIS viewing angles vary ±55° cross-track accompanied by solar illumination angle differences of up to 20° from edge to edge of the MODIS swath

(Huete et al. 1999). The variable scan angles cause MODIS pixel dimensions to change, cross-track and along-track. For example for 0° pixel dimension is 250 x 250 m; for 15° - it is 270 x 260 m; for 30° it is 350 x 285 m; and for 45° it is 610 x 380 m (Huete et al. 1999). This generates another source of error in the VI time-series data. Sun angles and variable pixel dimensions are illustrated in Literature Review-I section in Figure 2-3; and

- finally, spatial resolution of 250 m is suitable for characterizing the vegetation phenology for the FORWARD study area since average patch size is roughly about 0.4 $km^2$ which is greater than the individual pixel area of 0.0625 $km^2$.

### 3.5.2 MODIS current status

Wolfe (2003*a*) reported that Terra MODIS has been stable for over 26 months (after its launch) and there are no indications of problems other than failure of a power supply system, which was replaced. Current geolocation is very accurate (~50 m) and OBCs proved to be valuable for on-orbit characterization. Given this, deep-space maneuver is still needed to better characterize angle-of-incidence (AOI) response (Wolfe 2003*a*).

# Chapter 4

# Materials and Methods

## 4.1 Brief Description of the Study Area

This study has been carried out in 16 watersheds in the western Canadian Boreal Plain ecozone that extends southeast from north-eastern British Columbia through north-central Alberta and Saskatchewan to southwestern Manitoba. The geographic position of the study area lies at 54° 10' 6.6"-N Lat and 115° 34' 21"-W Long. Figure 4-1 shows the study area's location and the 16 test watersheds. Data about these watersheds has been collected as part of the FORWARD project.

The Boreal Plain ecozone is composed of a variety of forest species, including evergreen conifers such as Black spruce (*Picea mariana* (Mill.) BSP), White spruce (*P. glauca* (Moench) Voss), Lodgepole pine (*Pinus contorta* Dougl. ex Loud. Var. *latifolia Engelm*), Jack pine (*Pinus banksiana* Lamb), and deciduous hardwoods such as Balsam poplar (*P. balsamifera* L.) and Trembling aspen (*Populus tremuloides* Michx.). Soils in this ecozone are predominantly of sandy clay loam and many meters of deep unconsolidated clay loam glacial till, overlain primarily on sedimentary bedrock (Smith et al. 2003*b*). While the forest floor is generally covered with humus, the underlying strata are dominated by soils of Luvisolic order, and Gleysols, Brunisols, and Regosols are present as well (Ecological Stratification Working Group 1996). Organic and Gleysolic soils are associated with poor drainage (e.g. peatlands) areas while Luvisolic and Brunisolic soils occur on well drained sites (Strong and Leggat 1992). In addition, glaciofluvial, lacustrine, alluvial, and eolian deposits are also present, with textures that vary with the deposition process (Strong and Leggat 1992).

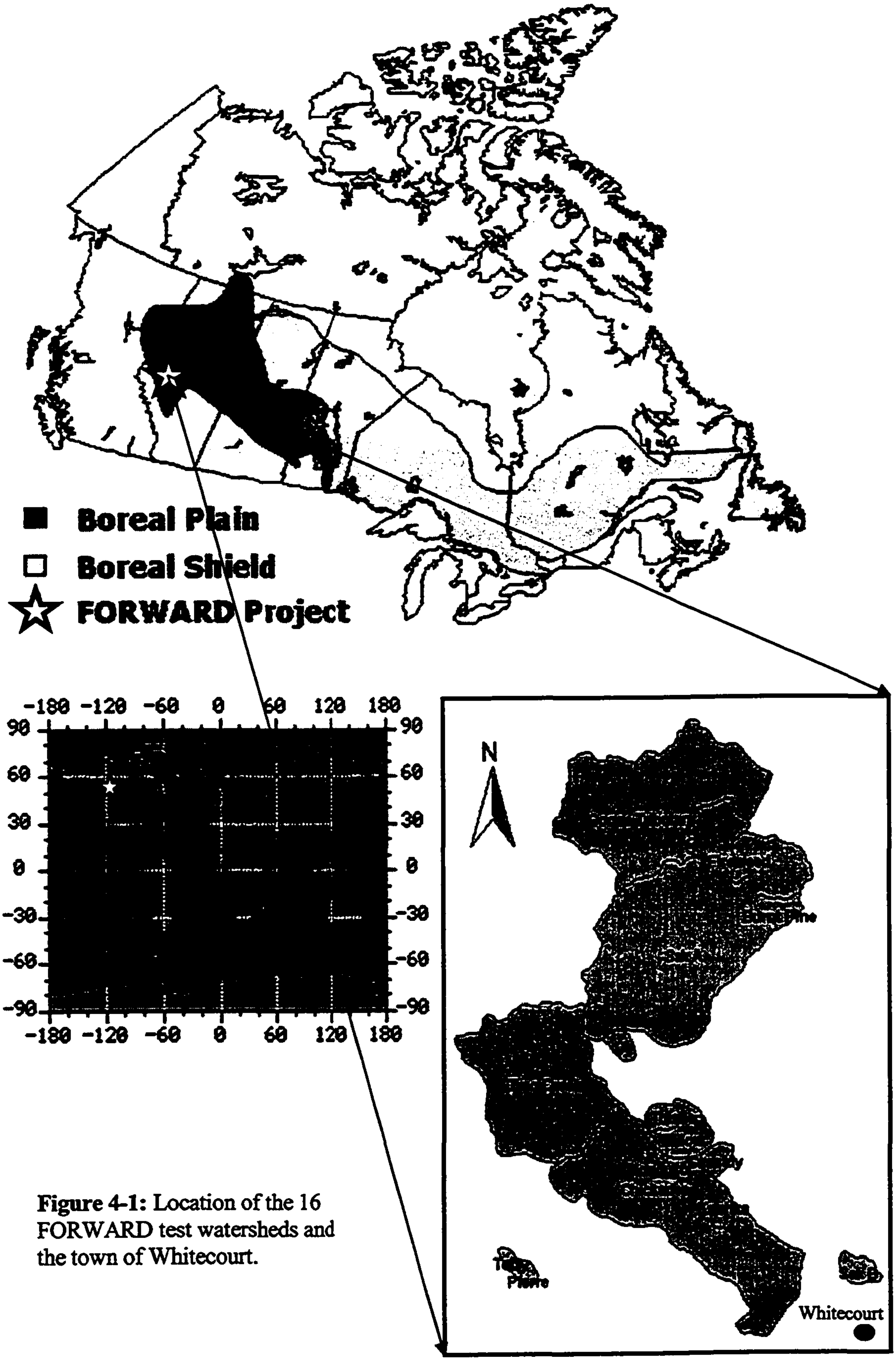


**Figure 4-1:** Location of the 16 FORWARD test watersheds and the town of Whitecourt.

Climate for this ecozone is continental, with long cold winters and short warm summers (Smith et al. 2003*a*) and relatively low annual precipitation (Strong 1992). Low albedo causes a greater heating of the overlying air mass relative to that over the Arctic Tundra, leading to a significant warming of the regional climate (Foley et al. 1994; Bonan et al. 1995). The mean July temperature is about 16 °C to 17 °C, with -20 °C being the mean January temperature (Saskatchewan's State of the Environment Report 1995); precipitation varies from 300 mm in Northern Alberta to 625 mm in southwestern Manitoba (Ecological Stratification Working Group 1996).

For the study area in particular, the highest mean monthly air temperatures and precipitations from 1939 to 1990, were recorded in July (Environment Canada 2003). The mean July air temperature at Whitecourt in Alberta, close to the study area location (54° 02'-N 115° 43'-W, Elevation: 1201 m) was 13.9 °C, and the mean July precipitation was 123.7 mm (Environment Canada 2003). The maximum 24-h precipitation of 91.8 mm was recorded on June 23 1985 (Environment Canada 2003). The mean air temperature for the period 1971 to 2000 at the Whitecourt airport location (54° 8'-N 115° 47'-W, Elevation: 782.4 m) in Alberta was -12.1 and 15.7 °C in January and July (lowest and highest for the year), respectively, and the mean annual precipitation was 577.7 mm, of which 30.8% occurred as snow (Environment Canada 2004*c*). The maximum 24-h precipitation of 98.6 mm was recorded on August 2 1989 (Environment Canada 2004*c*). Figure 4-1 illustrates the location of Whitecourt with respect to the study watersheds, where Environment Canada's weather stations are located.

## 4.2 Data Collection

### 4.2.1 Remote sensing data

A sequence of 4 years, from 2000 to 2003, of gridded MODIS VI (NDVI & EVI) dataset was used in this study. The dataset comes in Hierarchical Data Format - Earth Observing System (HDF-EOS), which is the standard archive format for EOS Data Information System (EOSDIS) products (MLST 2004). HDF-EOS is a multi-object file format and supports a variety of data types such as n-dimensional scientific data arrays, tables, text annotations, several types of raster images and their associated color palettes, and metadata. MODIS VI HDF-EOS file size is approximately 500 MB and consists of

11 Science data sets (SDSs), which are the actual data stored in array format (2-D, 3-D and even 4-D) (MLST 2004). Table 4-1 provides data field descriptions, data types, scale, valid range and fill values for the MODIS VI SDSs.

**Table 4-1:** Data filed descriptions of MOD13Q1 SDSs (Huete et al. 1999).

| Data field | Name | Data type | Scale | Valid range | Fill value |
|---|---|---|---|---|---|
| DataField_1 | 250 m 16 days NDVI | INT16 | 10000 | -2000 to 10000 | -3000 |
| DataField_2 | 250 m 16 days EVI | INT16 | 10000 | -2000 to 10000 | -3000 |
| DataField_3 | 250 m 16 days NDVI Quality | UINT16 | N/A | 0 to 65534 | 65535 |
| DataField_4 | 250 m 16 days EVI Quality | UINT16 | N/A | 0 to 65534 | 65535 |
| DataField_5 | 250 m 16 days red reflectance | INT16 | 10000 | 0 to 10000 | -1000 |
| DataField_6 | 250 m 16 days NIR reflectance | INT16 | 10000 | 0 to 10000 | -1000 |
| DataField_7 | 250 m 16 days blue reflectance | INT16 | 10000 | 0 to 10000 | -1000 |
| DataField_8 | 250 m 16 days MIR reflectance | INT16 | 10000 | 0 to 10000 | -1000 |
| DataField_9 | 250 m 16 days average view zenith angle | INT16 | 100 | -9000 to 9000 | -10000 |
| DataField_10 | 250 m 16 days average sun zenith angle | INT16 | 100 | -9000 to 9000 | -10000 |
| DataField_11 | 250 m 16 days average relative azimuth angle | INT16 | 10 | -3600 to 3600 | -4000 |

The first two layers of MOD13Q1 HDF-EOS file are the EVI and NDVI images. These are 16-day composite, re-sampled, 250 m spatial resolution, 4800 x 4800 rows/columns, cloud-free, pre-processed (see Figure 4-3) high quality imagery VI pixels, produced for each year since 2000. Although the valid range of NDVI or EVI is from -0.2 to 1, the values are scaled up by a factor of 10,000 with a fill value of -3000. Corresponding scales, valid ranges and fill values for other SDSs are also shown in the Table. The next two layers provide the NDVI and EVI per-pixel quality information followed by the four SDSs of reflectance data from which NDVI and EVI are derived. This provides users with the flexibility to change the co-efficient values in the EVI equation or modify the algorithms in relevance to the regional conditions. The last three SDSs provide the sun-canopy-sensor angles. This information is needed to know the variable scan geometry under which the pixel reflectances were measured by the MODIS sensor.

Each SDS (or layer) is a tile unit (fixed-area size) in the Sinusoidal (SIN) grid projection. The tile unit is the smallest unit of MODIS land data processed at any time and has an aerial extent of approximately 1200 km x 1200 km (10° x 10°). The tiles are defined in a global non-overlapping grid such that there are 460 tiles, of which 326 contain land pixels (LDOPE 2003*a*). Vertical and horizontal coordinates of each tile are represented in the product filename. The tile for the FORWARD study area was identified as h11v03. Sinusoidal grid bounding coordinates of the h11v03 tile are -140° to -93° 19' 49.8" Long, and 50° to 60° Lat (Wolfe 2003*b*). Bounding coordinates for all the tiles are provided online by Wolfe (2003*b*). Center point of this tile lies at 56° 10' 12" Lat, -114° 54' Lon. Figure 4-2 illustrates the MODIS tile grid system.

The name of the data set is "MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V004", with a short name of "MOD13Q1". L3 in the dataset name stands for level 3 whereas collection 4 (V004) refers to the reprocessed collection 1 and 3 MODLAND products, sensed from November 2000 to date, applying the latest available version of the science algorithm and using the best calibration and geolocation information available (LDOPE 2002). The filename is in the format; ESDT.AYYYYDDD.hHHvVV.CCC.YYYY DDDHHMMSS.hdf:

Where;

ESDT = Earth Science Data Type name (e.g., MOD13Q1)

YYYYDDD = MODIS acquisition year and Julian day

hHH = horizontal tile number (0-35)

vVV = vertical tile number (0-17)

CCC = collection number

YYYYDDDHHMMSS = processing year, Julian day and GMT time

hdf = suffix denoting HDF file

For example, the file name MOD13Q1.A2004161.h11v03.004.2004186084504.hdf is a MOD13Q1 product, acquired on the 161$^{st}$ day of the year 2004, with 11 as the horizontal and 3 as vertical tile coordinate (see Figure 4-2), product collection 004, and processed on the 186th day of the year 2004 at the time 8 hr 45 min 04 sec.

The MODIS VI HDF-EOS file provides quality information (Table 4-1) through QA metadata objects (in accompanying metadata files) that summarize tile level quality with several single words and numeric numbers (MLST 2004), thus enhancing the self-describing characteristics of each file and facilitating the archiving and searching of files. They provide the user with general information about the file contents, its characteristics and quality (through the QA) that is used to decide if the file is useful (MLST 2004). Parameter Value Language (PVL) is used to write the various metadata to the product file as: PARAMETER = VALUE. Table B-4 in Appendix B explains the meanings of metadata objects. In addition, the HDF-EOS file also contains two quality SDSs (see Table 4-1) that reflect quality on a pixel-by-pixel basis and thus it is useful for data analyses and application uses of the data (MLST 2004). Both the tile-level and pixel-level quality information are related such that pixel level information is summarized to develop the tile level quality information. The relationship Table B-2 in Appendix B provides VI quality bit combinations and their corresponding metadata objects.

### 4.2.2 Ancillary data

The ancillary data consists of Millar Western's Forest Products Ltd. Alberta Vegetation Inventory (AVI) and Blue Ridge Lumber Inc. AVI shape files, Environment Canada weather data, and FORWARD weather data. Software packages used to process the data include ERDAS Imagine 8.7, ESRI ARCGIS 8.2, ESRI ARCView, Matlab 6.5, SPSS 12.0 and Microsoft Office XP (Excel, Word, and Visio).

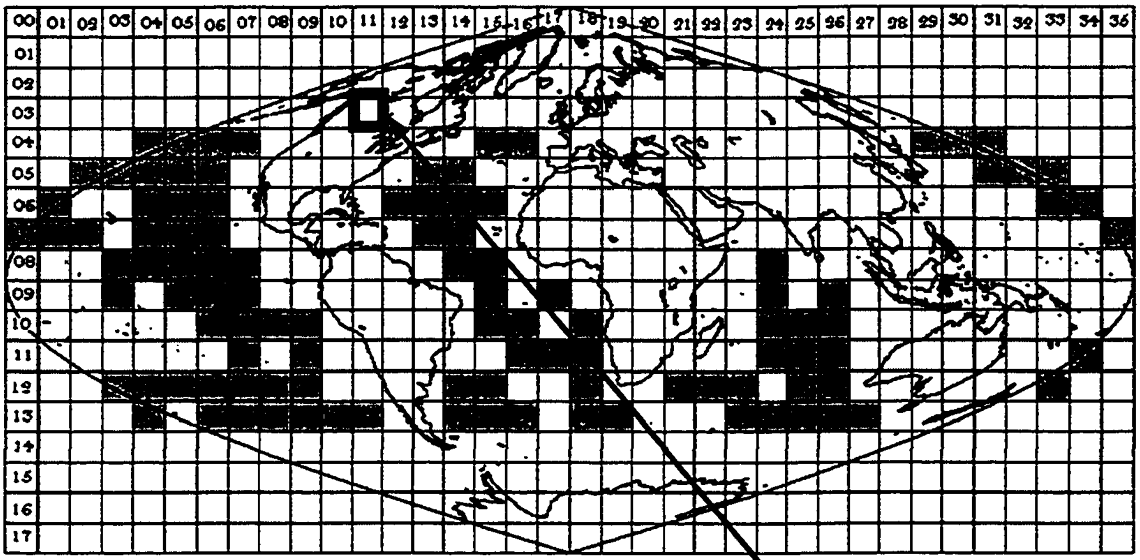

**Figure 4-2**: MODIS global tile grid. Shaded tiles are the ocean tiles, which are not produced. White tiles are where the land products are generated.

Tile of the study area: h11v03

## 4.3 Image Pre-processing

The pre-processing of the MOD13Q1 dataset has been done by the MODIS Land Science Team (MLST) and includes calibration, geolocation, corrections for molecular scattering, ozone absorption and aerosols, geometric and atmospheric corrections, data quality checks, and temporal compositing. Each of these processes has been discussed at length in the Literature Review-I section.

MODIS products are generated in a hierarchy of levels (Figure 4-3) (LDOPE 2003*a*). Level 0 (L0) refers to the at-sensor recorded "raw" intensities. These intensities are converted into calibrated, geolocated physical units of top-of-atmosphere (TOA) reflectances, which are called Level 1 (L1A and L1B) products. The L1 products are subsequently corrected for atmospheric effects to yield L2 products. Earth-gridded L2 surface reflectance is referred to as L2G surface reflectance. This product is an estimate of at-ground measured reflectances from the TOA measured radiances (to negate the effect of intervening atmosphere) recorded as Digital Counts (DCs) in each pixel of the satellite image. Surface reflectance product is a key product and serves as an input for all higher level land products (except for land surface temperature).

MOD13Q1 uses MODIS L2G surface reflectances, L2G pointer file, and the L2G geo-angle file as input to the VI equations. The surface reflectances are then temporally composited to generate the 16-day, 250 m VI product. Theoretically, a maximum of 64 observations can be generated by MODIS over a 16-day period because of the sensor orbit overlap and multiple observations in a single day. However, mean global cloud cover of 50-60% restricts this number from 0 to 64 with fewer observations near equatorial latitudes (MLST 2004). The number of acceptable pixels is typically less than 10 and often less than 5 (Huete et al. 2002). The MODIS VI algorithm applies a filter to the available L2 reflectance observations over the 16-day cycle based on quality, cloud and viewing geometry. MODIS, being a "whisk-broom" scanner, causes the pixel size to increase (see Figure 2-3 in Literature Review-I) with scan angle by as much as a factor of 4 (Huete et al. 2002). Therefore, nadir-view pixels possess minimal distortion. Cloud-contaminated and extremely off-nadir pixels are considered low quality while cloud free and nadir-view pixels with minimal residual atmospheric aerosol are considered good quality (van Leeuwen 1999). The VI compositing algorithm consists of three components: BRDF-C: Bidirectional Reflectance Distribution Function Composite, CV-MVC: Constrained-View angle Maximum Value Composite, and MVC: Maximum Value Composite. The number and quality of observations decide which compositing scheme is to be used. The Walthall semi-empirical BRDF model is utilized for the BRDF inversion scheme (Huete et al. 2002).

$$\rho_\lambda(\theta_v, \phi_s, \phi_v) = a_\lambda \theta_v^2 + b_\lambda \theta_v \cos(\phi_v - \phi_s) + c_\lambda \quad [3]$$

Where;

$\rho_\lambda$ = atmospherically corrected reflectance in band $\lambda$

$\theta_v$ = satellite view zenith angle

$\phi_s$ = satellite view azimuth angle

$\phi_v$ = solar azimuth angle

$a_{\lambda}$, $b_{\lambda}$, $c_{\lambda}$ are the model parameter coefficients (Walthall et al. 1985).

At least five good quality observations are needed to invert the model by a least square procedure. In case where less than five good observations are available, the CV-MVC scheme is used. For a single good observation, VI is computed from this observation. If no good observation is available after the initial data screening, the highest VI value is selected (MVC) regardless of data quality.

Since the FORWARD study area is located at high latitudes, it was anticipated that good quality observations would be available. During the initial processing of MODIS data, the BRDF module was found to be very sensitive to residual cloud cover. Based on reasoning that one contaminated value out of five will significantly bias the nadir-interpolated VI value, the BRDF module was turned off, though it may be reintroduced if the model can be properly adjusted (LDOPE 2004). Figure 4-3 illustrates the flow chart of the start to end processes occurring from the sensor activity to the final MOD 13Q1 product.

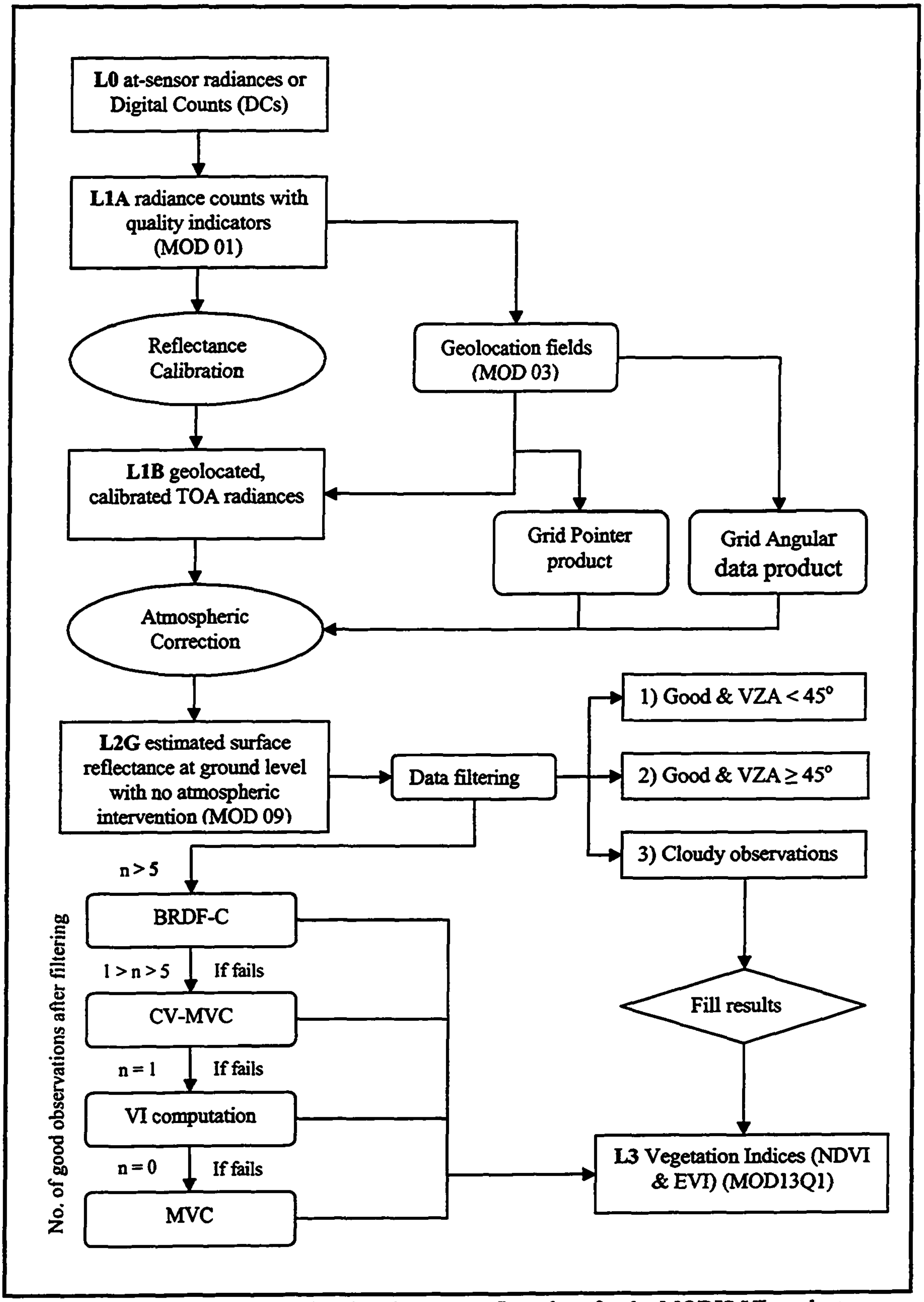


**Figure 4-3**: Schematic diagram showing the process flow chart for the MODIS VI product.

## 4.4 Methodology

An automated approach was used to derive the per-pixel VPMs from 4 year (2000-2003) time-series MODIS VI data. Only pixels covering the 16 test FORWARD watersheds were selected for analysis and results are reported as mean of VPMs computed over each watershed for each of the 4 years. Steps undertaken to carry out the analysis are shown in the Figure 4-4 and are explained below.

### 4.4.1 Data order and download

MODIS VI data (MOD13Q1) was ordered through EOS data gateway interface. The gateway can be accessed using MODIS' website http://modis.gsfc.nasa.gov/ through the "data" link. The Terra MODIS MOD13Q1 dataset was chosen in the search criteria and the coordinates of the study area were fed into the system. The search criteria retrieved the VI datasets from the years 2000 to early 2004. Data for 2004 has not been used in this study. 20 EOS-HDF files for year 2000 and 23 files for each year, 2001, 2002 and 2003, (total of 89 files with 89 metadata files) were ftp-pulled from NASA's server.

### 4.4.2 Data quality check

Once downloaded, data was checked for quality by metadata check, usefulness index check, and an online quality information check.

#### *4.4.2.1 Metadata check*

The accompanying metadata files were analyzed for quality control. For this purpose 'read_meta' algorithm was downloaded from the MODIS LDOPE tools distribution site (http://lpdaac.usgs.gov/landdaac/tools/ldope/index. asp) and installed on the computer. The program reads a set of specified metadata from MODIS Land HDF-EOS data product and writes the output to standard output. If no options are specified, all metadata are read (Land Processes Distributed Active Archive Center (LP DAAC) 2004). The program was run in the Microsoft Disk Operating System (MS DOS) environment to extract metadata objects of significance from the 89 metadata files. Each file has 18 metadata objects, the first 6 of which are called "QAFlags" and include Automatic quality flag, Operational quality flag, Science quality flag, and their explanations (see

Appendix B). The output was imported to MS Excel software and results are presented below. The command used to extract metadata is provided in Appendix A.

Another algorithm, 'unpack_sds_bits', was also downloaded from the MODIS LDOPE tools distribution site and used to decode the requested bit fields. The program writes to an output HDF file. The output SDS data type is uint8, uint16 or uint32 depending on the number of unpacked bits (LP DAAC 2004). The command was executed in the DOS environment and is provided in Appendix A. The problem encountered with this tool was that output file format was HDF and not EOS-HDF, which resulted in loss of the projection information of the tile. Re-projection of the tile to SIN grid involves a re-sampling procedure which will translate to the loss of some VI information in the tile. Therefore, the results of this algorithm were not used in the subsequent analysis.

Automatic quality flag for the seven images in year 2000 i.e. from February 18 2000 to May 24 2000 was set to "suspect" while the rest of the 82 images had a "passed" status. This flag is the result of an automatic quality assessment performed during product generation. The flag is set to "passed" if QAPercentMissingData < 5%; set to "suspect" if QAPercentMissingData > 5% or < 50%; and set to "failed" if QAPercentMissingData > 50%, where the "QAPercentMissingData" is also a QA metadata object and is described in Appendix B.

The Operational quality flag, which indicates if the data are corrupted in the transfer, archival, and retrieval processes, was set to "passed". The Science quality flag, which indicates manual, science-QA performed by VI Science Computing Facility (SCF) personnel (MLST 2004), was set to "being investigated" for collection 4 VI data. Currently the Science quality metadata are not being updated in the metadata files and so the values must be checked online at the LDOPE (2003*b*) website. The percent interpolated data, missing data, out-of-bound data, not-produced-due-to-other-reasons data and not-produced-due-to-cloud data were zero. All data were sea processed and tiles consisted of 100% land pixels.

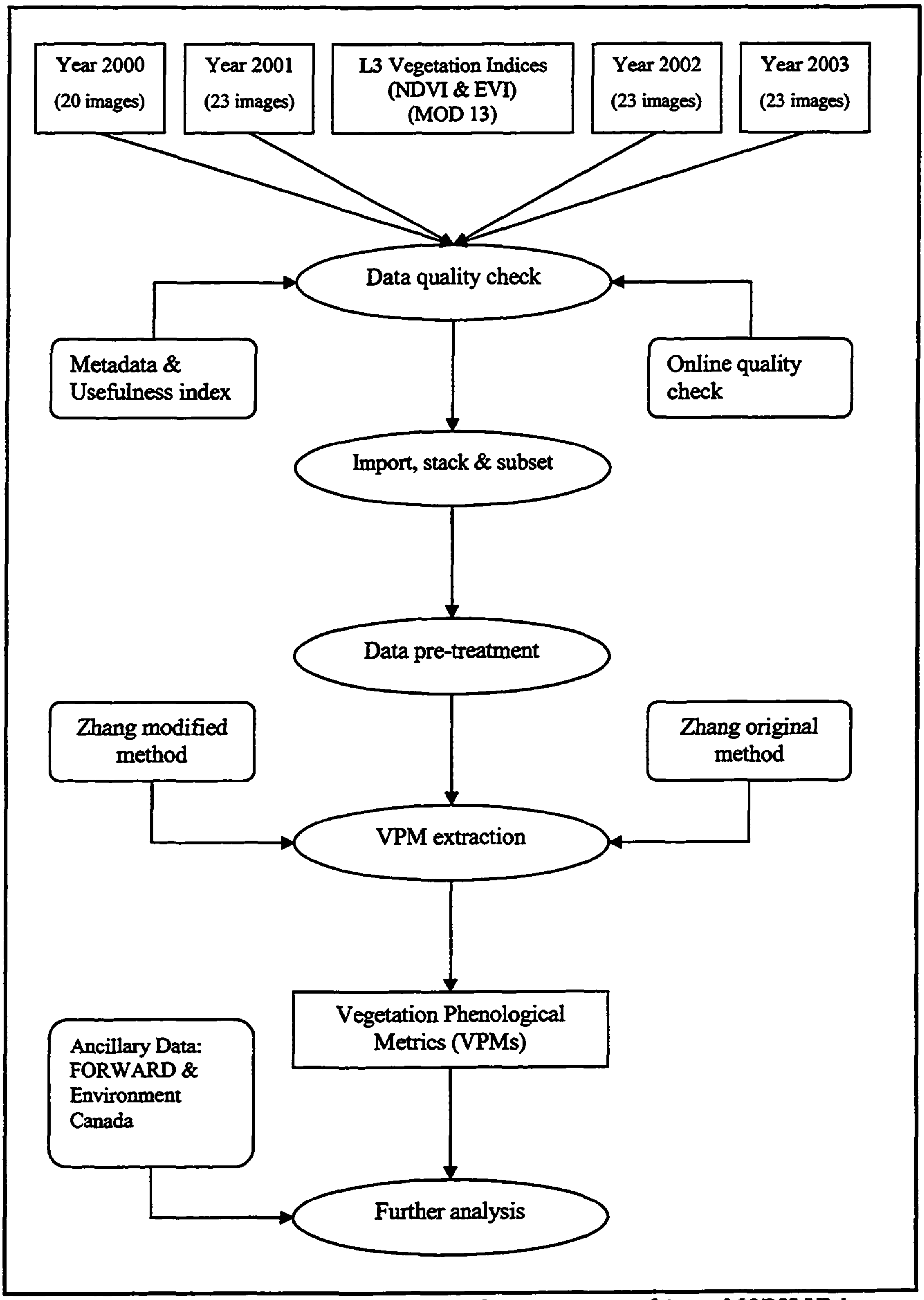


**Figure 4-4**: Process flow chart of VPM derivation from a sequence of 4 year MODIS VI data.

Figure 4-5 and 4-6 illustrate percent good quality pixels and percent cloud cover, respectively, in the 89 acquired image tiles for the year 2000-2003. Five images were found to have less than 60% (arbitrary set threshold) good quality pixels, i.e. the image tiles created on June 10 2001, October 16 2002, November 1 2002, October 16 2003, and November 1 2003 had 34%, 43%, 54%, 52%, and 53% good quality pixels, respectively. Four images were found to have greater than the acceptable standard of 10% cloud cover i.e. the image tiles created on June 10 2001, October 16 2001, March 22 2002, and December 3 2002 had 23%, 11%, 14%, and 14% cloud cover, respectively. In addition, data was also checked for the Product Generation Executive (PGE) version, which consists of one or more science code executables, control scripts and support files. It is a three digits number, the first one is unique to the product collection (since the data is collection 4 so the number starts from 4), the second reflects a major science code change such as an algorithm change, and the third represent a minor code change such as bug fixes etc (LDOPE 2003*c*). Figure 4-7 suggests that there were no major science code changes in the VI algorithm since the year 2000.

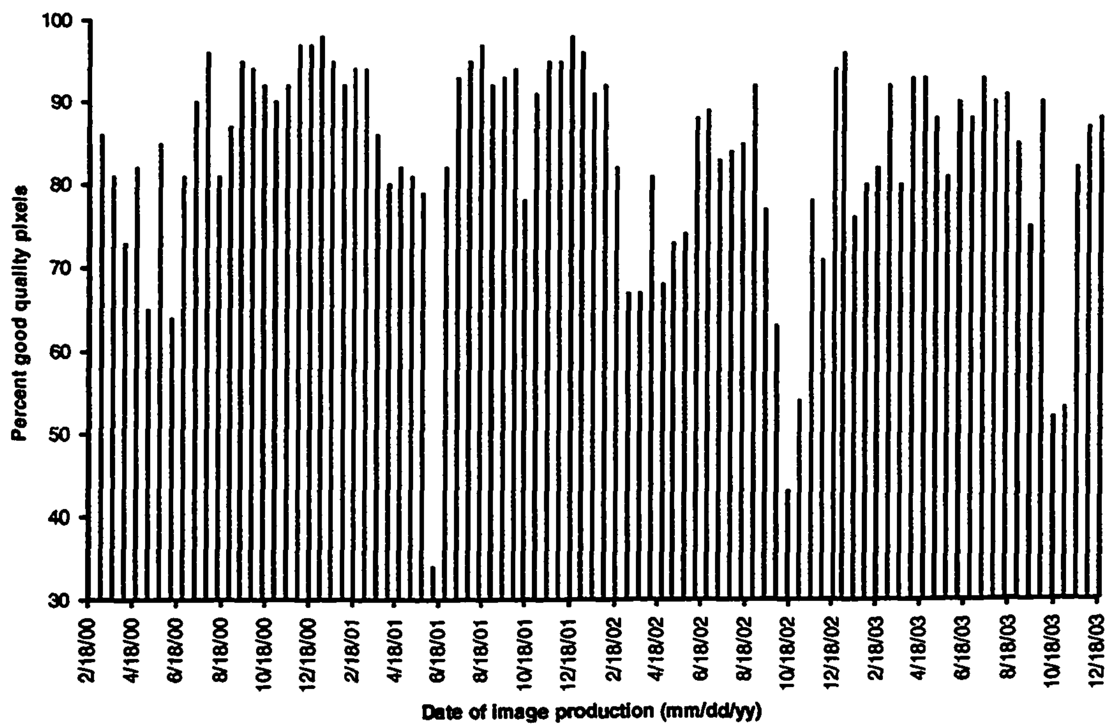


**Figure 4-5**: Percent good quality pixels in tiles of 89 images for the year 2000-2003.

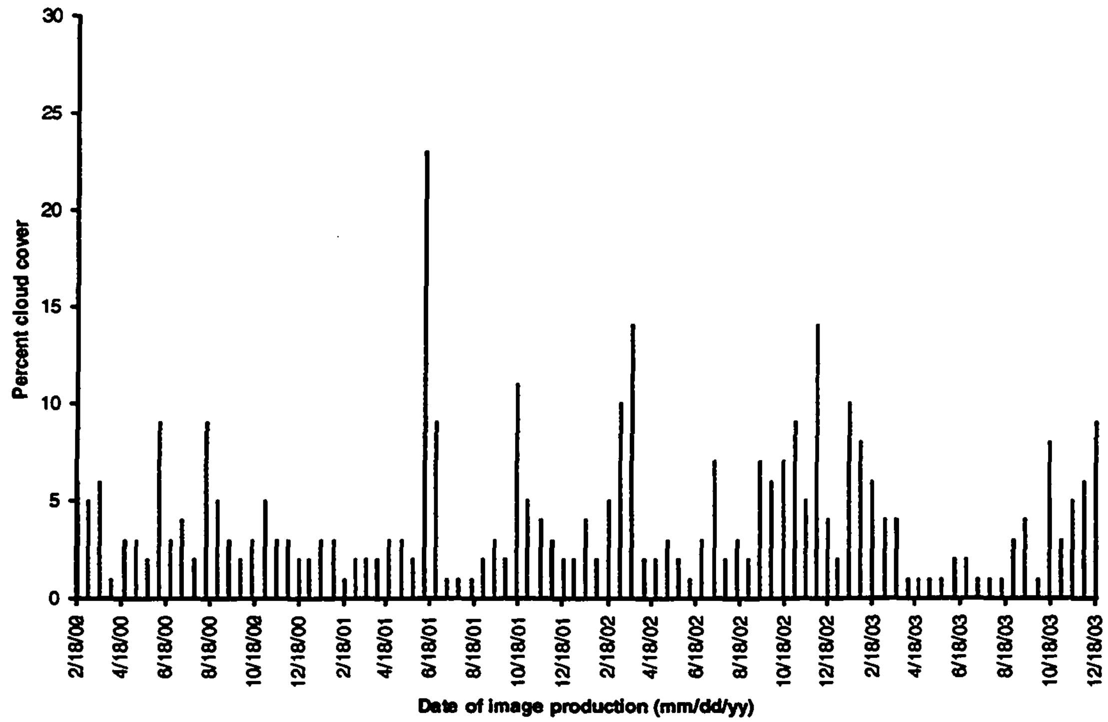


**Figure 4-6**: Percent cloud cover over tiles for 89 images for the year 2000-2003.

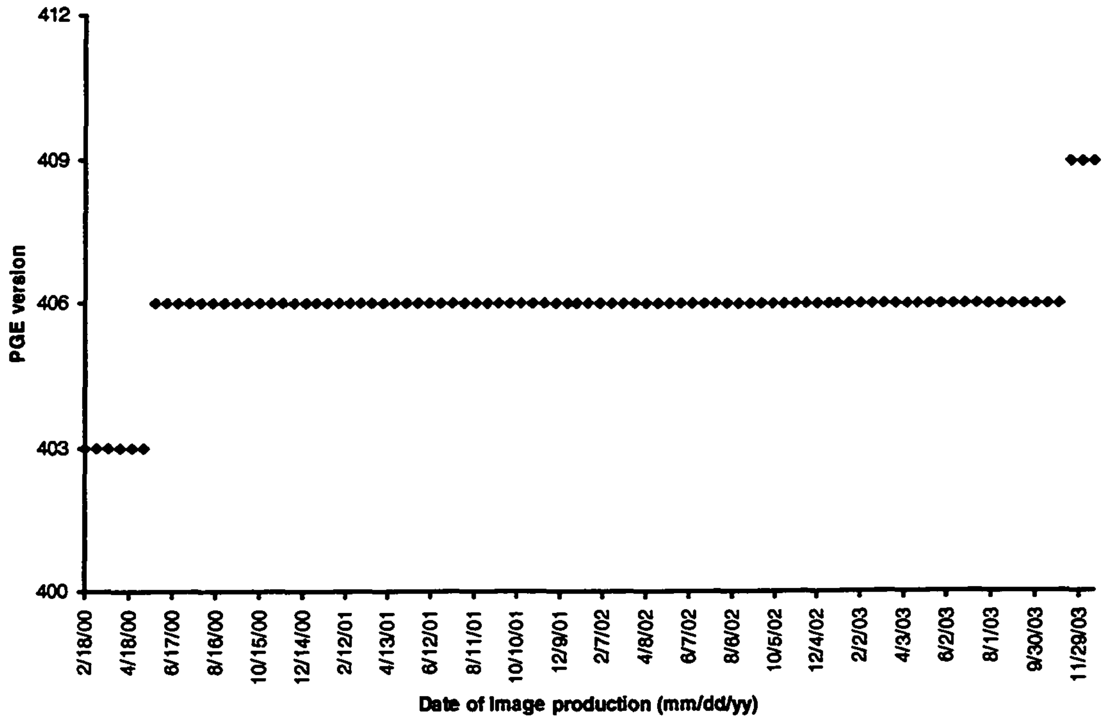


**Figure 4-7**: Product version history of 89 images for the year 2000-2003.

#### *4.4.2.2 Usefulness index check*

Usefulness index is the 2nd bit-field in QA SDS and a superior quality indicator. Its value for a pixel reflects the variable conditions of aerosol quantity, atmospheric correction, cloud cover, shadow, and sun-target-viewing geometry. A specific score is assigned to each condition and the sum of all the scores gives a usefulness index value for the pixel. Table B-3 in Appendix B provides the usefulness index scaling method.

The metadata objects QAPERCENTPOORQ250M16DAYNDVI and QAPERCE NTPOORQ250M16DAYEVI are computed as sums of the NDVI and EVI usefulness indices and indicate, respectively, the percent frequency distributions of the NDVI and EVI quality (MLST 2004). Their values reflect 16 quality levels from 'perfect' (highest) to 'not useful' (lowest) in the descending order from left to right. Figure 4-8, 4-9, 4-10 and 4-11 present the frequency distribution of EVI and NDVI quality over the image tiles for the year 2000, 2001, 2002 and 2003, respectively. There are no "perfect" or "high" quality pixels (first two levels) but the majority of the pixels are "good" quality from April till November of each year. The start and the end of the year, however, are dominated by "acceptable" quality pixels. Since this study will utilize pixels from the growing season of vegetation, the pixels employed are "good" quality for EVI and NDVI. Moreover, FORWARD watersheds are located near the center of the MODIS scan tile, which translates to smaller zenith and scan angles. This reduces the risk of faulty VI pixel values due to larger scan angle. For instance, a high view angle would explain the high EVI value. Sun angles were visually inspected to check for any unusual VPM behavior and majority of the angles were found to be in acceptable range.

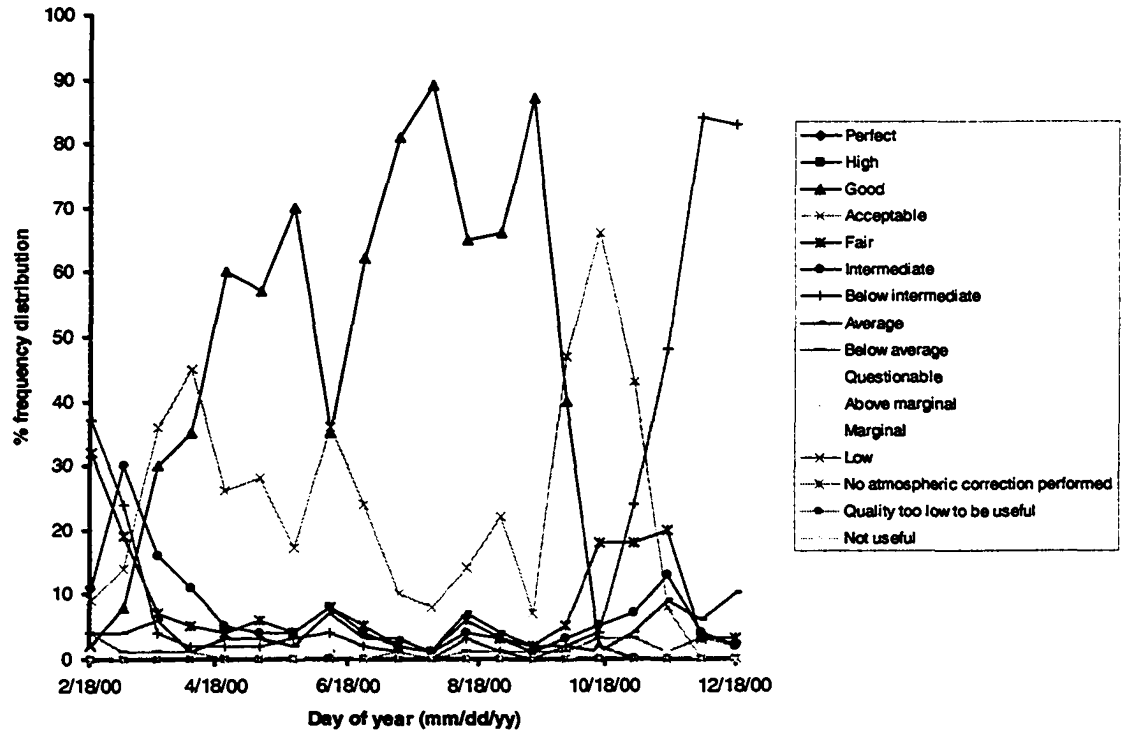


**Figure 4-8**: Frequency distribution of EVI and NDVI quality for the year 2000.

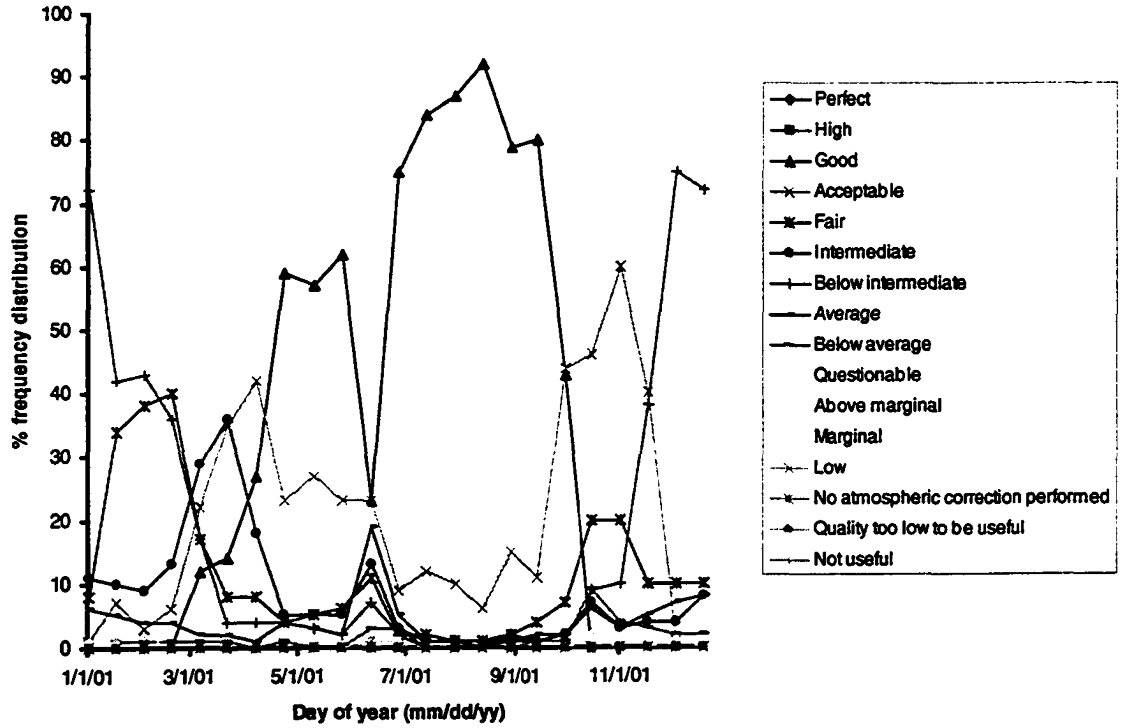


**Figure 4-9**: Frequency distribution of EVI and NDVI quality for the year 2001.

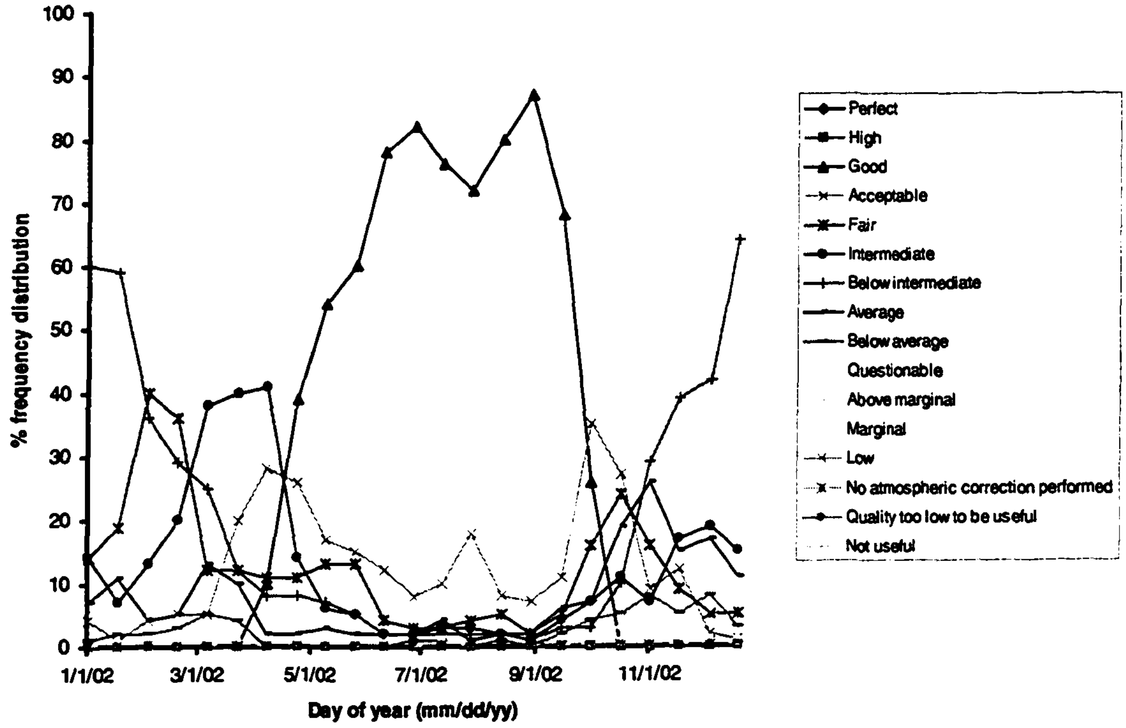


**Figure 4-10:** Frequency distribution of EVI and NDVI quality for the year 2002.

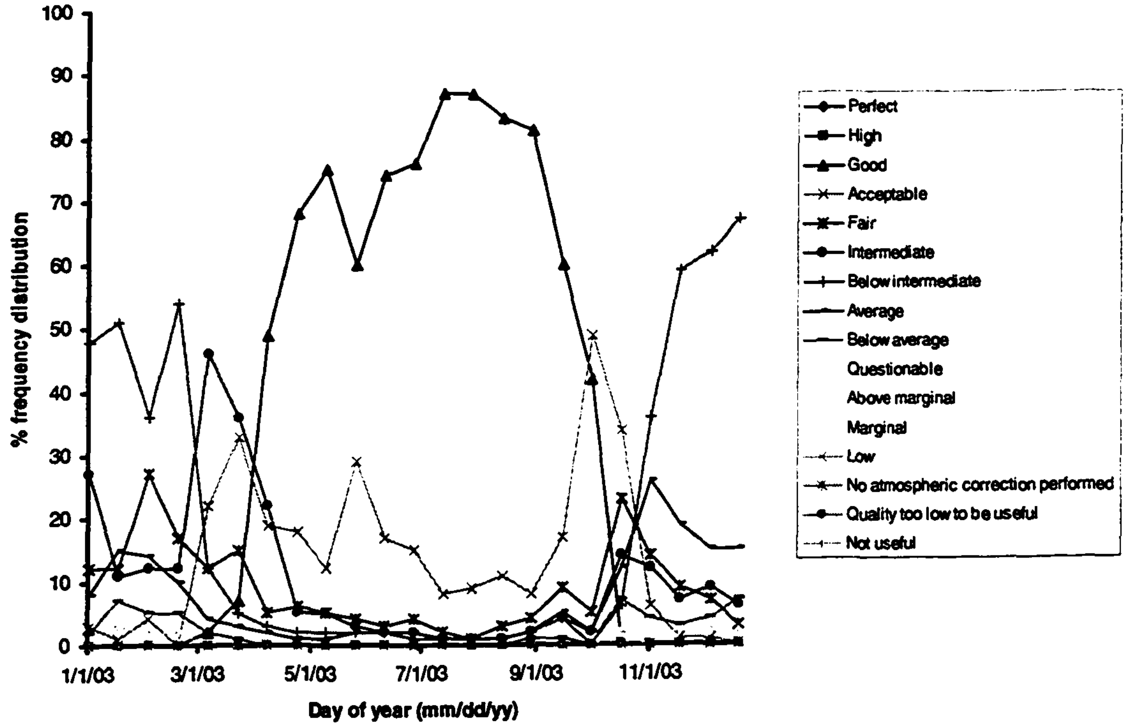


**Figure 4-11:** Frequency distribution of EVI and NDVI quality for the year 2003.

#### *4.4.2.3 Known product issues website (LDOPE 2004)*

The following issues identified by LDOPE (2004) with VI data were taken into consideration:

1) Beginning with Julian day 257, 2000 only the CV-MVC method is used due to complications with the BRDF method.

2) The 16 day compositing periods for the MOD13Q1 VI product are aligned with January 1, which translates to 22.8 (365/16 = 22.8) compositing periods in a year. The end-of-year shortened compositing period (0.8 x 16 = 12 days) is supplemented with data from the beginning of the subsequent year, while maintaining alignment with January 1. This results in a data overlap between end-of-year and beginning-of-year compositing periods.

3) Double line artifact were seen in collection 4 of MOD13 VI data on data Julian day 170 2002 and 219 2002 over western Canada due to a geolocation problem caused by an orbit drag makeup maneuver performed on the same dates (see Figure 4-12).

4) Stripping was observed in some of the MOD13 VI data due to an aerosol retrieval problem related to band 7 stripping in the MOD09 reflectance product (see Figure 4-12).

5) Blocky EVI and NDVI retrieval was observed due to the presence of high aerosol in daily surface reflectance products (MOD09) causing the algorithm to use data from different days than the one used for the neighboring pixels (see Figure 4-12).

6) Prior to data Julian day 017, 2001 and PGE versions 2.3.1, unrealistically high EVI values over snow, ice and clouds were observed. However, an update to the EVI algorithm has rectified the problem and since the PGE version of collection 4 data (used for this study) is 4.0.3 and above. This is a not a concern here.

**Figure 4-12**: Three images showing artifacts such as double line (left), stripping (center), and blockiness (right). The images are ndvi.MOD13Q1.A2002161.h09v05.004.2003241004232 (left), ndvi.MOD13A1.A2003257.h11v09.004.2003285030319 (center), ndvi.MOD13Q1.A2003081.h21v06.004.2003110132223 (right).

#### *4.4.2.4 Data quality conclusions*

As a result of metadata, usefulness index and online quality check, it was concluded that the data must be pre-treated to extract VPMs. Neither any data was screened nor was any of 89 layers rejected on the basis of data quality check as no appropriate criteria/threshold value could be developed. In addition, the metadata objects reflected the averaged conditions of all pixels in the tile, which may not be the representative of the FORWARD Area of Interest (AOI) pixels since FORWARD watershed (study AOI) pixels constitute only 0.05% of the whole tile pixels (see Table 4-3). Metadata analysis was based on the assumption that the error distribution is uniform throughout the tile area e.g. cloud cover of 23% doesn't necessarily imply that it is 23% over the FORWARD study area, though it was assumed so. It may be less or more than that. The better approach is to derive AOI specific metadata but, this is thought to be out of scope for this research work. Nevertheless, the tile-level data quality check combined with the online check provided a good idea of data issues.

### 4.4.3 Data import, stack and subset

After quality checks, 89 MOD13Q1 files were imported into ERDAS Imagine GIS software. All the 11 SDSs in each HDF-EOS file were converted to 11 image (.img) files, the ERDAS Imagine standard raster file format. EVI images for each year were then stacked using the "Image Stack" module and subsetted using the AOI shape file of the watersheds. The same procedure was repeated for each SDS.

### 4.4.4 Data pre-treatment

Time-series VI data comprised of 23 16-day composite VI images for each year, from 2000 to 2003. Per-pixel VPM extraction required pre-treatment of this data. For this purpose the stacked-subsetted VI data were exported as Binary Interleaved (.bil) files to Matlab and treated using Wardlow et al. (2004) method. Based on the reasoning that it is very unlikely for the onset of greenup to occur before March 21 and the end of greenup to occur after November 17 for this study area, time-series VI data were divided into two parts and treated differently; as follows:

#### *4.4.4.1 Tail treatment*

Eight composite periods from 1 to 5 and 21 to 23 were designated as time-series tail. First five composite periods 1 to 5 spanning January 1 to March 21 of each year were designated as front tail, while the last three, 21 to 23 spanning November 17 to December 31 were designated as end tail. Tails were vigorously smoothed, since the extraction of phenological metrics was concerned only with the vegetation growth period and thus, variation occurring in these segments was deemed as of little to no use (regardless of its source) in the determination of onset dates for vegetation in the Boreal plain ecozone. An extremely conservative latent (or background) VI threshold of 0.15, which was determined by visual inspection of pixel-level time series plots, was used to screen tail pixels with anomalous values suppressed due to pre-processing artifacts (clouds, aerosols, signal noise etc.). It was anticipated that eliminating the temporal data variability induced by these sub-background VI values should theoretically do no harm to the analysis (Kastens 2004, Verbal communication).

Front and end tail data was subjected to flat smoothing and values were replaced by the median computed over the first five VI values (for front tail) and last three VI values (for end tail).

#### *4.4.4.2 Interior treatment*

15 composite periods from 6 to 20 spanning March 22-November 16 were designated as time series interior. For the interior treatment, all the local minima VI values, xi (where i represents the time period) were identified such as $x_{i-1} > x_i < x_{i+1}$.

The minima are points where the value of the function is less than both the adjacent predecessor (xi-1) and successor (xi+1) points. The interior minima VI values were replaced with the minimum value of $x_{i-1}$ or $x_{i+1}$. This treatment, however, had no impact on the valid peak and increasing or decreasing interior VI values. The VI peaks were considered valid because CV-MVC instead of MVC was used to generate the VI values, and it does not select maximum VI values. Though the interior treatment may have replaced some legitimate VI values, identifying the onset of greenup was primarily dependent on the initial monotonic greenup segment of each VI curve, which, theoretically, should have had no substantial legitimate VI minima values (Wardlow et al. 2004). The true end-of-segment VI minima values, however, were negatively impacted by the treatment. This had negligible impact on the subsequent VPM extraction (Kastens 2004, Verbal communication). Figure 4-13 and 4-14 illustrate the results of data treatment of the mean EVI and NDVI computed over 16 watersheds, respectively, while Figures 4-15 and 4-16 illustrate the results for the mean EVI and NDVI computed over the Sak A watershed, respectively.

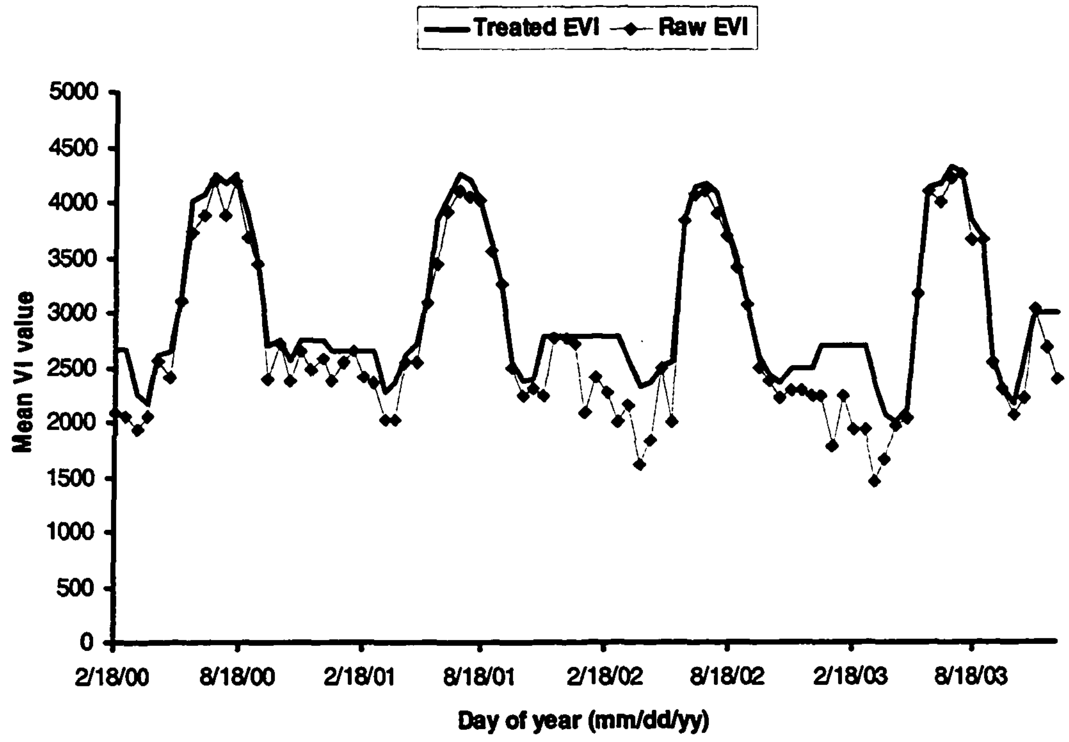


**Figure 4-13**: Comparison of before versus after treatment for mean EVI over 16 watersheds.

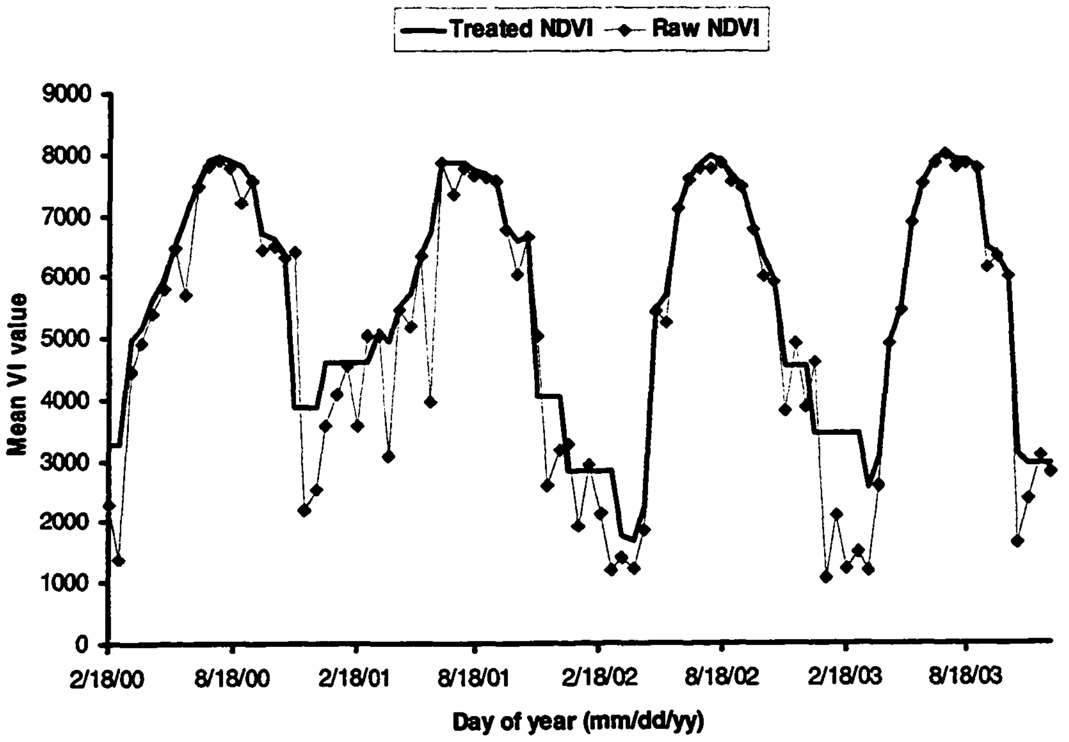


**Figure 4-14**: Comparison of before versus after treatment for mean NDVI over 16 watersheds.

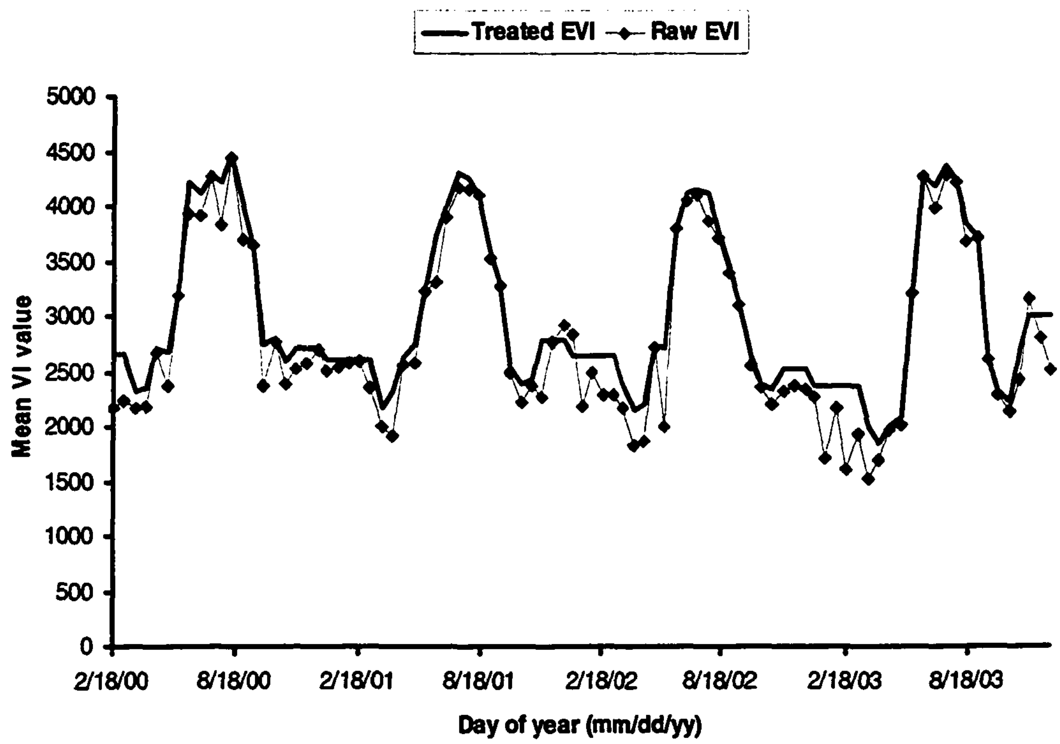


**Figure 4-15:** Comparison of before versus after treatment for mean EVI over Sak A watershed.

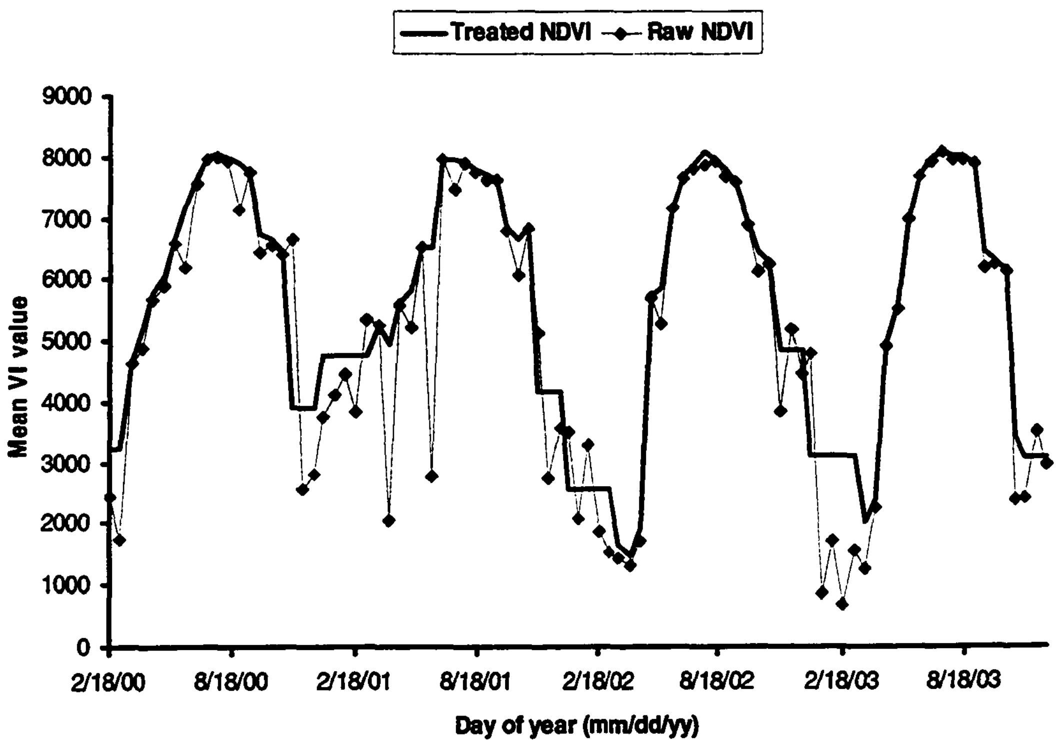


**Figure 4-16:** Comparison of before versus after treatment for mean NDVI over Sak A watershed.

### 4.4.5 Extraction of Vegetation Phenological Metrics (VPMs)

A total of 10 VPMs were derived from the MODIS 4 year (2000-2003) pre-processed, pre-treated VI data versus time curve. These VPMs are adapted from the phenological parameters of Reed et al. (1994), Lloyd (1990) and Malingreau (1986). A typical forest phenological cycle has the same basic elements: from null in winter (or low) to full photosynthetic status in late spring and back to senescent in the fall as shown in Figure 4-17 and different species vary in phase and intensity of the peak. VPMs are aimed at characterizing and capturing this variation in each year's seasonality of the time series data. Table 4-2 provides the VPMs and their phenological interpretations and Figure 4-17 provides a further understanding of VPMs.

**Table 4-2**: Vegetation Phenological Metrics (VPMs) and their descriptions.

| Metrics | Description of metrics |
|---|---|
| Onset of Greenup (OG) | Beginning date of photosynthetic activity that corresponds to the start of growth development which begins as soon as climate conditions are favorable. This is the x-axis value at the first point of inflection of the time series VI curve |
| Onset VI value | Level of photosynthetic activity at which the onset occurred. This is the y-axis value at the first point of inflection of the time series VI curve |
| Peak date | Date of maximum photosynthetic activity. This is the x-axis value at the peak of the time series VI curve |
| Peak VI value | Maximum level of photosynthetic activity. This is the y-axis value at peak of the time series VI curve |
| End of Greenup (EG) | End date of the photosynthetic activity or dormancy, which is a state of suspended growth and metabolism. This is the x-axis value at the second point of inflection of the time series VI curve |
| End VI value | Level of photosynthetic activity at which the end of greenup occurred. This is the y-axis value at the second point of inflection of the time series VI curve |
| Length of growing season | Duration of photosynthetic activity. This is the linear distance between the two points of inflection parallel to the x-axis |
| Time integrated VI value | Net primary production and the accumulation of biomass over the growing season. This is the area under the curve |
| Rate of greenup | Acceleration of photosynthetic activity. This corresponds to the positive slope of the curve (dx/dt) |
| Rate of senescence | Deceleration of photosynthetic activity. This corresponds to the negative slope of the curve (-dx/dt) |

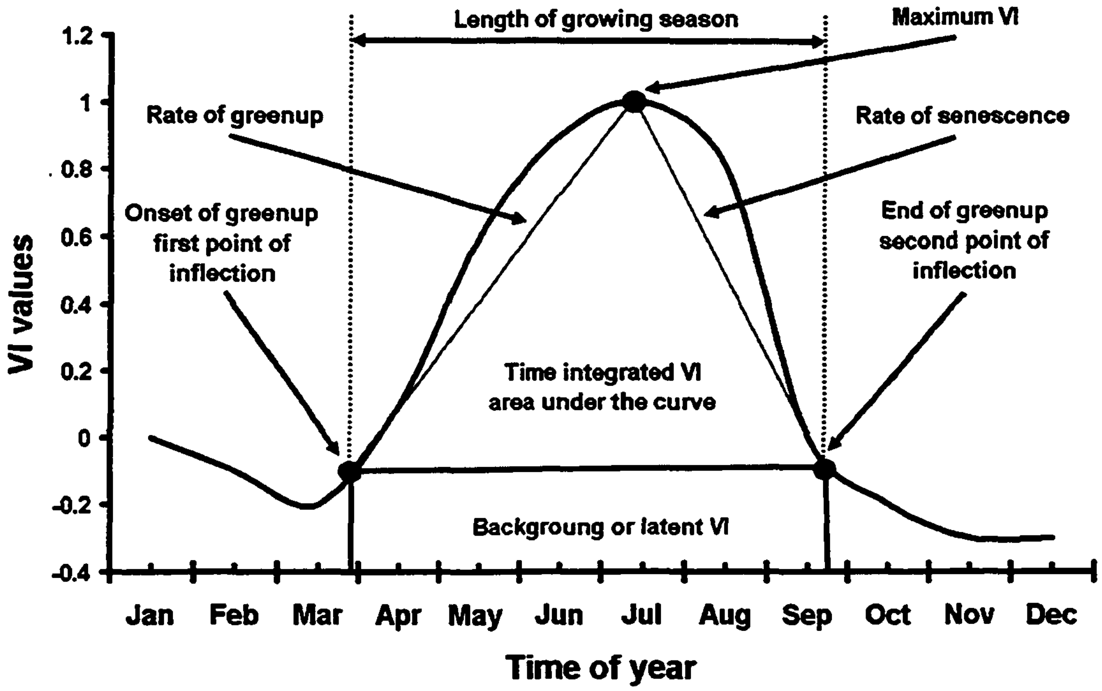


**Figure 4-17**: Derivation of VPMs from the yearly VI temporal profile.

Past efforts using time-series VI data to identify key phenological transition dates: onset of greenup (OG) and end of greenup (EG) are summarized in Literature Review-II section. The approaches adopted in this study to extract OG from the VI time series curve are the Zhang approach and the Zhang modified approach. Zhang approach identifies the extreme points where rate of change in curvature of the fitted logistic models to the VI time-series data, changes sign as the phenological transition dates (OG and EG). This method uses the function of the form as given by Zhang et al. (2003):

$$y(t) = \frac{c}{1+e^{a+bt}} + d \qquad [4]$$

Curvature, $K$ at any time $t$ can be computed using:

$$K = \frac{d\alpha}{ds} = -\frac{b^2 cz(1-z)(1+z)^3}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}} \qquad [5]$$

The rate of change of curvature, K', is then:

$$K' = b^3 cz \left\{ \frac{3z(1-z)(1+z)^3\left[2(1+z)^3 + b^2c^2z\right]}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{5}{2}}} - \frac{(1+z)^2\left(1+2z-5z^2\right)}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}} \right\} \quad [6]$$

Where;

$t$ = time in days

y($t$) = VI value at time $t$

$a$ and $b$ = fitting parameters

$c + d$ = maximum VI value

$d$ = background or latent VI value

$z = e^{a+bt}$

$\alpha$ = the angle in radians of the unit tangent vector at time $t$ along a differentiable curve

s = unit length of the curve

The modified approach goes a step further by computing another point of maximum second derivative of the fitted logistic function and identifies the transition dates as the average of the two points.

Once the OG was identified using both approaches, the EG was extracted using a similar method as for the OG but the data was treated in reverse chronological sequence. Data were assumed to have one mode (i.e. one growth cycle), with OG being determined by moving inward from the beginning of the year and the EG determined by moving inward from the end of the year. Since the MODIS dataset for the year 2000 is not complete (data is generated from February 18 and not from January 1 as with the years 2001, 2002 and 2003), the "date" metrics (i.e. OG date, EG date, and maximum VI date) from 2000 were scaled as if the 2000 data had a complete stack with 23 layers instead of 20. This allowed data from the year 2000 to be compared directly with values from other years. The date metrics were snapped to 16-day MODIS composite periods, i.e. the 'composite periods' were used as the time/date measuring units. For example, a pixel having an OG date value of 8 means that onset occurred during period 8 of 16-day raw imagery collection time frame. Values less than zero were replaced with zero and all zero values were deemed as either background, non-vegetated, or problem pixels for which no metrics were computed. Other VPMs were calculated only when the OG and EG dates were both defined, and in this case only when the EG date occurred more than one period after the OG date.

The Zhang algorithm, through use of a continuous, best-fit function, allows one to speculate OG down to as much temporal detail as desired (down to fractions of a second and beyond, as far as machine precision permits). Though, it is easy to argue either way regarding the significance of estimating onset beyond the 16-day resolution of the data, it really depends on how the information is being used. In this study, the OG and EG metrics were calculated down to the day (daily OG and EG), in addition to down to the 16-day composite period. However, this "drilling down" luxury could not be afforded with other VPMs such as with the "maximum VI date" VPM, as this was derived directly from the VI time series. Maximum VI date was measured instead in composite periods and reported in days using the relation that 1 composite period = 16 days. While the OG and OE VI values could also not be calculated down to the day, these VPMs can be interpolated to arrive at daily values.

Finally, the length of the growing season, measured in composite periods and reported in days, was computed by subtracting the daily OG date from the daily EG date (length of growing season = daily OG date – daily EG date + 1). The rates of greenup and senescence, measured in VI units/composite period, were computed as straight line slopes (dx/dt) from the OG to maximum VI and maximum VI to EG point (see Figure 4-17), respectively.

### 4.4.6 Further analysis

Once the metrics were computed for each pixel in the study area, tables of results were generated from the VPM images and are presented in the next chapter. This involved computing the mean and standard deviation of VPMs over each watershed. The sample size is variable since the watersheds' sizes and the number of pixels comprising each is variable. Table 4-3 presents the number of 250 x 250 m (0.0625 $km^2$ area) pixels covering each watershed. As a result of variable scan angles and image compositing, the final MODIS VI pixel resolution comes out to be 231 x 231 m (0.0534 $km^2$). Based on this resolution, the total number of pixels covering the FORWARD study area will slightly increase to 13861 from 11836 (see Table 4-3). Table 4-3 gives an idea of how many pixels were used to compute the mean of VPMs over each watershed. The general trend observed during any image analysis exercise is that statistical means computed over larger pixel samples tend to reduce random errors. This implies that smaller watershed VPMs are more vulnerable to errors propagation since a small number of pixels have been used to compute means, and one or two anomalous values can significantly bias the statistic. In the next step, results were subjected to such statistical procedures as ANOVA, the Pearson correlation coefficient computation and Multiple Comparison Tests (MCTs) to derive meaningful conclusions.

**Table 4-3:** Area and number of pixels for each watershed.

| Watersheds | Area ($km^2$) | No. of pixels (250 x 250m) | No. of pixels (231 x 231m) |
|---|---|---|---|
| Goose | 150.57 | 2410 | 2822 |
| Sak A | 233.93 | 3743 | 4384 |
| Chickadee | 155.19 | 2483 | 2908 |
| Two Creek | 129.39 | 2070 | 2425 |
| Burnt Pine | 7.66 | 123 | 143 |
| Fireweed | 5.69 | 91 | 107 |
| 1A | 5.10 | 82 | 96 |
| Cassidy | 5.87 | 94 | 110 |
| Kashka | 3.91 | 63 | 73 |
| Millions | 2.43 | 39 | 45 |
| Mosquito | 3.07 | 49 | 57 |
| Pierre | 2.58 | 41 | 48 |
| Sak B | 7.04 | 113 | 132 |
| Thistle | 9.01 | 144 | 169 |
| Toby | 2.63 | 42 | 49 |
| Willow | 15.57 | 249 | 292 |
| All area | 739.65 | 11836 | 13861 |

# Chapter 5

## Results and Discussion

A suite of 10 per-pixel VPMs, using both Zhang and Zhang modified approaches, was developed using 4 year time-series MODIS VI data. The analysis was carried over for each pixel (a total of 11836) in the16 FORWARD test watersheds, but for the ease of presentation and further analysis as well as making generalizations, measure of central tendency and dispersion of the VPMs were computed over each watershed. The statistical mean of VPMs computed for the vegetated pixels in each of the 16 watersheds based on four comparative approaches is given in Table 5-1 to 5-4; the standard deviation is presented in Appendix C as Table C-1 to C-4 for the years 2000 to 2003. The OG and EG dates are measured on a daily basis and reported in calendar date units. Composite periods were used as the units of measurement for the peak VI date and length of growing season metrics; they are translated into units of calendar dates and number of days, respectively, for ease of presentation. VI value metrics (OG VI, EG VI and peak VI value) and time integrated VI value are presented in the same units as were measured; VI units, which vary from 0 to 1 in the treated data (and -0.2 to 1 in the data before treatment) are scaled up by a factor of 10,000. The rates of greenup and senescence metrics are measured and reported in the VI units per composite period multiplied by 10,000. Because of the tail treatment, no OG dates could appear before composite period 6 (March 21) and no EG dates could occur after composite period 20 (November 17) for all of the four approaches.

For discussion purposes, VPMs derived from EVI and Zhang method are represented by EVIz, EVI and Zhang modified method by EVIm, NDVI and Zhang method by NDVIz, and NDVI and Zhang modified method by NDVIm (see Figure 5-1). These four comparative approaches to derive four sets of VPMs were statistically analyzed to check for differences among the four approaches.

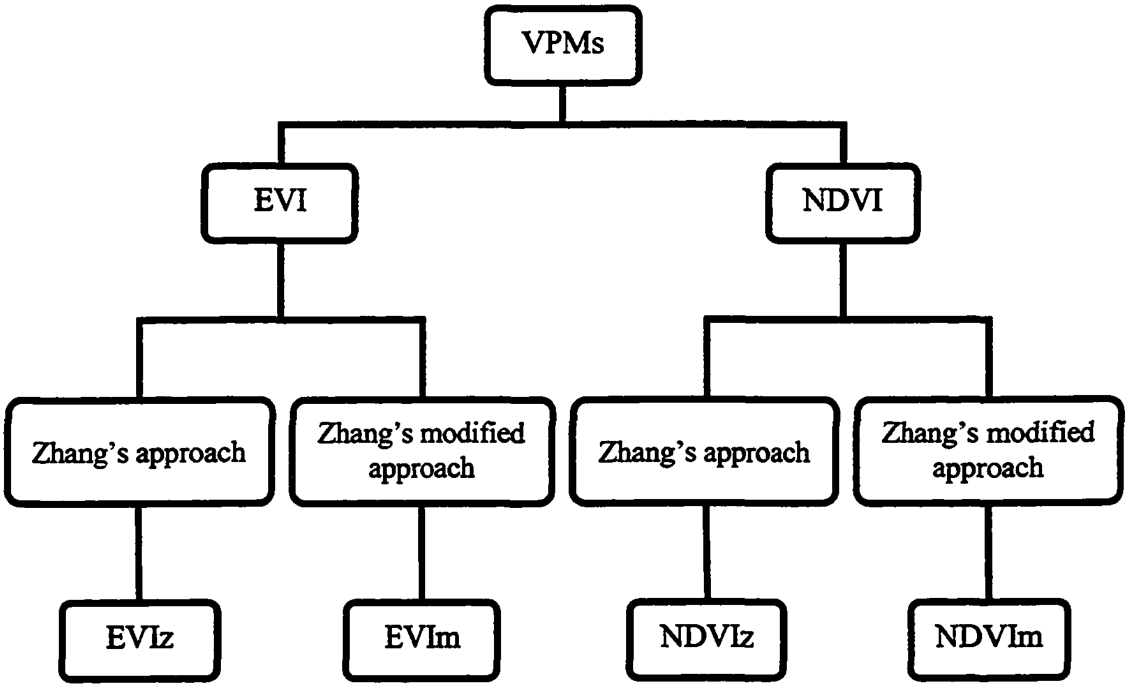


**Figure 5-1**: Four comparative approaches to derive VPMs.

Mean VPMs shown in Table 5-1 to 5-4 were first yearly stratified and the averages and variances were then determined for the resulting sample size of 16 observations (one for each watershed) for each of the 10 VPMs in each year 2000, 2001, 2002 and 2003. ANOVA at alpha level 0.05 revealed that the differences in average values (computed for N = 16) for each of the VPMs among the four methods are highly significant ($P < 0.001$) as shown in Table 5-5. The Levene statistic, used as a test of homogeneity of variances, confirmed that all the methods have equal variances and thus verified the assumptions of ANOVA. Tukey HSD and Bonferroni Multiple Comparison Tests (MCTs) were applied to compare each method with the other and both of the tests yielded the same results. Homogenous subsets of VPMs based on Tukey HSD MCT were established and given in Table 5-6.

**Table 5-1**: Mean of EVIz based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date[1] | End date[1] | Peak date[1] | Onset value[2] | End value[2] | Peak value[2] | Length[3] | Time-int.VI[2] | Rt of green up[4] | Rt of sensecence[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 5/27 | 9/12 | 7/20 | 2932 | 3355 | 5734 | 109 | 39834 | 913 | 714 |
| | 2001 | 5/8 | 9/21 | 8/6 | 3030 | 2918 | 4528 | 137 | 40952 | 346 | 411 |
| | 2002 | 4/30 | 9/23 | 7/4 | 2987 | 2848 | 5039 | 147 | 43252 | 628 | 361 |
| | 2003 | 5/25 | 8/31 | 7/5 | 2526 | 2974 | 5103 | 98 | 35909 | 1051 | 483 |
| Burnt pine | 2000 | 5/26 | 10/10 | 7/24 | 3122 | 2985 | 6030 | 138 | 50005 | 920 | 583 |
| | 2001 | 5/10 | 10/3 | 7/26 | 2670 | 2779 | 5237 | 147 | 46191 | 643 | 490 |
| | 2002 | 5/3 | 10/2 | 7/18 | 3041 | 3063 | 5159 | 153 | 47254 | 619 | 395 |
| | 2003 | 5/6 | 9/13 | 6/29 | 2471 | 2814 | 5557 | 131 | 41961 | 1143 | 476 |
| Cassidy | 2000 | 5/9 | 9/21 | 7/20 | 2956 | 3596 | 6034 | 135 | 48012 | 764 | 532 |
| | 2001 | 5/24 | 9/15 | 7/12 | 3279 | 3110 | 5997 | 115 | 41261 | 1052 | 664 |
| | 2002 | 4/16 | 10/8 | 7/5 | 3459 | 2803 | 5467 | 176 | 51169 | 690 | 418 |
| | 2003 | 5/11 | 9/7 | 7/19 | 2691 | 2858 | 5396 | 120 | 40926 | 687 | 606 |
| Chickadee | 2000 | 5/16 | 9/23 | 7/20 | 2760 | 3009 | 5299 | 130 | 42171 | 723 | 505 |
| | 2001 | 5/21 | 9/21 | 7/10 | 3060 | 2814 | 5348 | 124 | 40156 | 838 | 471 |
| | 2002 | 5/4 | 9/28 | 7/8 | 2774 | 2632 | 4985 | 148 | 42052 | 757 | 409 |
| | 2003 | 5/5 | 9/8 | 7/18 | 2543 | 2698 | 4901 | 127 | 38290 | 644 | 555 |
| Fireweed | 2000 | 6/9 | 9/22 | 8/12 | 2540 | 2596 | 4566 | 106 | 31367 | 562 | 600 |
| | 2001 | 5/5 | 9/17 | 7/24 | 2477 | 2525 | 4987 | 136 | 36826 | 725 | 577 |
| | 2002 | 4/30 | 9/25 | 7/22 | 2268 | 2367 | 4397 | 149 | 34969 | 709 | 430 |
| | 2003 | 4/30 | 9/13 | 7/23 | 1720 | 2548 | 4557 | 137 | 33606 | 600 | 528 |
| Goose | 2000 | 6/11 | 9/14 | 8/1 | 2357 | 2593 | 4409 | 96 | 31693 | 628 | 474 |
| | 2001 | 5/8 | 9/20 | 7/31 | 2300 | 2385 | 4443 | 136 | 33822 | 504 | 503 |
| | 2002 | 5/7 | 9/14 | 7/17 | 2356 | 2431 | 4388 | 130 | 32202 | 741 | 439 |
| | 2003 | 5/3 | 9/19 | 7/27 | 2037 | 2296 | 4352 | 139 | 32198 | 583 | 525 |
| Kashka | 2000 | 5/13 | 9/18 | 7/27 | 2461 | 2784 | 4303 | 129 | 34728 | 438 | 384 |
| | 2001 | 5/10 | 9/12 | 7/9 | 2744 | 2476 | 4705 | 126 | 35117 | 659 | 463 |
| | 2002 | 4/30 | 8/19 | 7/5 | 2488 | 2680 | 4255 | 112 | 33633 | 530 | 360 |
| | 2003 | 4/24 | 9/2 | 7/12 | 2538 | 2444 | 4564 | 132 | 32820 | 748 | 479 |
| Millions | 2000 | 5/7 | 9/5 | 7/10 | 3032 | 3508 | 4807 | 122 | 36575 | 596 | 414 |
| | 2001 | 5/22 | 8/19 | 6/27 | 3372 | 3214 | 4878 | 91 | 31937 | 685 | 449 |
| | 2002 | 5/2 | 8/24 | 6/6 | 3368 | 3178 | 4745 | 115 | 35238 | 731 | 260 |
| | 2003 | 4/29 | 8/21 | 6/30 | 3188 | 2949 | 4369 | 114 | 34084 | 583 | 330 |
| Mosquito | 2000 | 5/16 | 10/4 | 7/11 | 2660 | 2791 | 5457 | 143 | 43757 | 817 | 462 |
| | 2001 | 5/24 | 9/27 | 7/1 | 2701 | 2440 | 5457 | 127 | 39787 | 1067 | 496 |
| | 2002 | 4/15 | 10/5 | 6/21 | 2800 | 2554 | 5028 | 174 | 43385 | 834 | 361 |
| | 2003 | 5/9 | 9/12 | 7/19 | 2315 | 2393 | 4981 | 127 | 36747 | 743 | 637 |
| Pierre | 2000 | 5/31 | 9/14 | 8/3 | 2639 | 3018 | 4563 | 107 | 33353 | 528 | 512 |
| | 2001 | 5/21 | 9/25 | 8/2 | 3286 | 2685 | 4538 | 128 | 32654 | 514 | 490 |
| | 2002 | 5/12 | 10/4 | 7/22 | 2905 | 2635 | 4400 | 146 | 35786 | 604 | 376 |
| | 2003 | 5/1 | 9/13 | 7/16 | 2516 | 2837 | 4831 | 136 | 36945 | 608 | 604 |
| Sak A | 2000 | 5/27 | 9/29 | 7/28 | 2836 | 2874 | 5225 | 126 | 41041 | 709 | 546 |
| | 2001 | 5/12 | 9/23 | 7/26 | 2715 | 2663 | 4845 | 134 | 39245 | 562 | 478 |
| | 2002 | 4/28 | 9/27 | 7/12 | 2668 | 2599 | 4905 | 153 | 42046 | 669 | 426 |
| | 2003 | 5/11 | 9/9 | 7/13 | 2329 | 2658 | 4910 | 123 | 36683 | 800 | 504 |
| Sak B | 2000 | 5/5 | 10/10 | 8/6 | 2208 | 2740 | 5642 | 160 | 48320 | 644 | 615 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2001 | 5/15 | 10/9 | 7/15 | 2430 | 2718 | 5810 | 147 | 45503 | 972 | 538 |
| | 2002 | 5/9 | 10/5 | 7/20 | 2218 | 2573 | 4985 | 150 | 40228 | 804 | 427 |
| | 2003 | 4/24 | 9/30 | 7/28 | 1682 | 2303 | 5159 | 160 | 39024 | 720 | 663 |
| Thistle | 2000 | 5/20 | 9/8 | 7/16 | 2942 | 3054 | 4937 | 112 | 36097 | 672 | 544 |
| | 2001 | 5/22 | 9/5 | 7/12 | 3069 | 2767 | 4820 | 108 | 35987 | 606 | 457 |
| | 2002 | 5/1 | 9/18 | 7/13 | 2887 | 2719 | 4874 | 142 | 39350 | 655 | 484 |
| | 2003 | 5/17 | 8/22 | 7/15 | 2417 | 2824 | 4744 | 97 | 34162 | 704 | 505 |
| Toby | 2000 | 5/16 | 9/23 | 8/3 | 2671 | 3251 | 5411 | 130 | 42901 | 616 | 658 |
| | 2001 | 6/7 | 9/30 | 7/14 | 3134 | 2858 | 5211 | 116 | 39085 | 929 | 408 |
| | 2002 | 4/26 | 9/30 | 7/18 | 3176 | 2701 | 5473 | 158 | 45616 | 668 | 514 |
| | 2003 | 4/30 | 9/9 | 7/20 | 2726 | 2673 | 4856 | 132 | 37323 | 601 | 606 |
| Two creek | 2000 | 5/18 | 9/20 | 7/28 | 2696 | 3062 | 5360 | 126 | 41427 | 709 | 598 |
| | 2001 | 5/19 | 9/24 | 7/23 | 2973 | 2699 | 4844 | 129 | 39424 | 537 | 447 |
| | 2002 | 5/4 | 10/1 | 7/14 | 2761 | 2626 | 5098 | 150 | 41867 | 760 | 458 |
| | 2003 | 5/10 | 9/9 | 7/10 | 2408 | 2732 | 5028 | 123 | 38156 | 847 | 497 |
| Willow | 2000 | 5/15 | 9/30 | 7/19 | 2742 | 2845 | 5548 | 138 | 43942 | 829 | 531 |
| | 2001 | 5/15 | 10/1 | 7/17 | 2885 | 2588 | 5367 | 141 | 42607 | 802 | 507 |
| | 2002 | 5/3 | 10/8 | 7/3 | 3106 | 2568 | 5359 | 159 | 45675 | 820 | 408 |
| | 2003 | 5/5 | 9/8 | 7/24 | 2476 | 2649 | 5278 | 126 | 40041 | 732 | 667 |

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

**Table 5-2**: Mean of EVIm based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date[1] | End date[1] | Peak date[1] | Onset value[2] | End value[2] | Peak value[2] | Length[3] | Time-int.VI[2] | Rt of green up[4] | Rt of sensecence[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 5/31 | 9/7 | 7/24 | 3129 | 3363 | 5584 | 100 | 35925 | 1186 | 771 |
| | 2001 | 5/14 | 9/17 | 8/6 | 3213 | 2887 | 4513 | 126 | 38930 | 363 | 436 |
| | 2002 | 5/4 | 9/15 | 7/4 | 3272 | 2851 | 5081 | 135 | 41332 | 805 | 399 |
| | 2003 | 5/28 | 8/26 | 7/6 | 2975 | 2928 | 5103 | 91 | 34228 | 1165 | 516 |
| Burnt pine | 2000 | 5/31 | 10/1 | 7/24 | 3503 | 3038 | 6013 | 124 | 45970 | 1102 | 602 |
| | 2001 | 5/15 | 9/26 | 7/27 | 3083 | 2793 | 5236 | 135 | 44037 | 732 | 498 |
| | 2002 | 5/7 | 10/3 | 7/18 | 3215 | 2914 | 5165 | 150 | 45043 | 745 | 405 |
| | 2003 | 5/8 | 9/7 | 7/2 | 2750 | 2768 | 5565 | 123 | 40403 | 1238 | 551 |
| Cassidy | 2000 | 5/18 | 9/13 | 7/19 | 3390 | 3626 | 6039 | 119 | 43514 | 984 | 563 |
| | 2001 | 5/28 | 9/3 | 7/13 | 3588 | 3197 | 5991 | 99 | 36825 | 1713 | 850 |
| | 2002 | 4/19 | 9/30 | 7/10 | 3788 | 2794 | 5436 | 165 | 49187 | 792 | 467 |
| | 2003 | 5/15 | 9/4 | 7/19 | 2913 | 2846 | 5411 | 113 | 39792 | 756 | 625 |
| Chickadee | 2000 | 5/22 | 9/16 | 7/21 | 3007 | 3037 | 5280 | 118 | 39154 | 941 | 540 |
| | 2001 | 5/26 | 9/11 | 7/10 | 3358 | 2874 | 5348 | 109 | 36870 | 1239 | 526 |
| | 2002 | 5/8 | 9/20 | 7/10 | 3074 | 2649 | 4954 | 135 | 39959 | 860 | 431 |
| | 2003 | 5/9 | 9/3 | 7/18 | 2804 | 2686 | 4899 | 118 | 36919 | 697 | 572 |
| Fireweed | 2000 | 6/16 | 9/19 | 8/12 | 2769 | 2598 | 4539 | 96 | 29007 | 725 | 610 |
| | 2001 | 5/16 | 9/10 | 7/27 | 2810 | 2571 | 4924 | 118 | 34527 | 848 | 585 |
| | 2002 | 5/8 | 9/18 | 7/22 | 2611 | 2332 | 4390 | 134 | 33403 | 791 | 444 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2003 | 5/15 | 9/8 | 7/26 | 2256 | 2583 | 4549 | 117 | 31424 | 683 | 560 |
| Goose | 2000 | 6/17 | 9/9 | 8/2 | 2610 | 2528 | 4398 | 86 | 29625 | 777 | 499 |
| | 2001 | 5/20 | 9/13 | 7/31 | 2413 | 2386 | 4424 | 116 | 31076 | 645 | 520 |
| | 2002 | 5/16 | 9/7 | 7/18 | 2499 | 2385 | 4364 | 116 | 31040 | 772 | 455 |
| | 2003 | 5/14 | 9/13 | 7/29 | 2303 | 2239 | 4343 | 123 | 30931 | 601 | 555 |
| Kashka | 2000 | 5/20 | 9/12 | 7/28 | 2629 | 2850 | 4328 | 115 | 32780 | 498 | 409 |
| | 2001 | 5/18 | 9/3 | 7/8 | 2909 | 2471 | 4699 | 109 | 31533 | 1044 | 520 |
| | 2002 | 5/5 | 8/10 | 7/3 | 2759 | 2668 | 4279 | 98 | 30954 | 707 | 399 |
| | 2003 | 4/30 | 8/28 | 7/10 | 2721 | 2432 | 4610 | 121 | 31766 | 904 | 491 |
| Millions | 2000 | 5/14 | 9/6 | 7/12 | 3248 | 3421 | 4820 | 116 | 34856 | 682 | 459 |
| | 2001 | 5/26 | 8/8 | 6/25 | 3639 | 3303 | 4880 | 75 | 28215 | 907 | 524 |
| | 2002 | 5/4 | 8/25 | 6/15 | 3623 | 3084 | 4541 | 114 | 34812 | 703 | 254 |
| | 2003 | 5/2 | 8/17 | 7/1 | 3423 | 2943 | 4347 | 109 | 32185 | 610 | 327 |
| Mosquito | 2000 | 5/23 | 9/27 | 7/11 | 2898 | 2800 | 5474 | 128 | 41108 | 1090 | 481 |
| | 2001 | 5/29 | 9/15 | 7/1 | 3055 | 2572 | 5452 | 110 | 35789 | 1619 | 563 |
| | 2002 | 4/18 | 9/28 | 6/22 | 2832 | 2490 | 4952 | 164 | 42052 | 1111 | 377 |
| | 2003 | 5/12 | 9/6 | 7/19 | 2694 | 2328 | 4981 | 118 | 35859 | 807 | 648 |
| Pierre | 2000 | 6/5 | 9/13 | 8/4 | 2760 | 2940 | 4523 | 102 | 32106 | 735 | 576 |
| | 2001 | 5/25 | 9/21 | 7/30 | 3402 | 2646 | 4553 | 120 | 32419 | 666 | 510 |
| | 2002 | 5/15 | 9/29 | 7/22 | 3231 | 2685 | 4443 | 138 | 35281 | 638 | 365 |
| | 2003 | 5/7 | 9/8 | 7/18 | 2747 | 2824 | 4790 | 125 | 35530 | 648 | 639 |
| Sak A | 2000 | 6/1 | 9/23 | 7/29 | 3085 | 2885 | 5215 | 114 | 38440 | 906 | 570 |
| | 2001 | 5/20 | 9/16 | 7/27 | 2999 | 2692 | 4829 | 120 | 36538 | 684 | 501 |
| | 2002 | 5/4 | 9/19 | 7/14 | 3015 | 2592 | 4887 | 140 | 39994 | 767 | 449 |
| | 2003 | 5/16 | 9/5 | 7/14 | 2682 | 2652 | 4905 | 113 | 35394 | 882 | 518 |
| Sak B | 2000 | 5/15 | 10/2 | 8/6 | 2592 | 2823 | 5642 | 142 | 45368 | 730 | 634 |
| | 2001 | 5/23 | 9/28 | 7/16 | 2892 | 2763 | 5810 | 129 | 42234 | 1253 | 578 |
| | 2002 | 5/16 | 9/27 | 7/20 | 2659 | 2575 | 4971 | 136 | 38560 | 914 | 455 |
| | 2003 | 5/4 | 9/26 | 7/27 | 2095 | 2270 | 5194 | 146 | 38270 | 805 | 685 |
| Thistle | 2000 | 5/25 | 9/4 | 7/19 | 3089 | 2986 | 4933 | 103 | 34660 | 821 | 579 |
| | 2001 | 5/25 | 8/28 | 7/15 | 3304 | 2823 | 4809 | 97 | 33446 | 790 | 535 |
| | 2002 | 5/3 | 9/13 | 7/13 | 3093 | 2733 | 4882 | 133 | 38776 | 856 | 496 |
| | 2003 | 5/23 | 8/18 | 7/16 | 2647 | 2816 | 4728 | 89 | 32765 | 759 | 534 |
| Toby | 2000 | 5/27 | 9/19 | 8/3 | 2919 | 3231 | 5315 | 116 | 38571 | 857 | 668 |
| | 2001 | 6/9 | 9/20 | 7/15 | 3450 | 2857 | 5217 | 104 | 35698 | 1261 | 451 |
| | 2002 | 4/30 | 9/24 | 7/17 | 3414 | 2785 | 5480 | 148 | 43760 | 839 | 538 |
| | 2003 | 5/5 | 9/5 | 7/22 | 3035 | 2755 | 4822 | 124 | 35901 | 570 | 615 |
| Two creek | 2000 | 5/23 | 9/15 | 7/30 | 2929 | 3057 | 5308 | 116 | 38351 | 890 | 652 |
| | 2001 | 5/25 | 9/17 | 7/24 | 3215 | 2723 | 4839 | 117 | 36982 | 678 | 469 |
| | 2002 | 5/9 | 9/23 | 7/16 | 3113 | 2652 | 5083 | 138 | 40163 | 864 | 488 |
| | 2003 | 5/13 | 9/4 | 7/11 | 2735 | 2727 | 5020 | 115 | 36957 | 901 | 517 |
| Willow | 2000 | 5/22 | 9/22 | 7/20 | 3101 | 2916 | 5550 | 123 | 41137 | 1050 | 550 |
| | 2001 | 5/21 | 9/22 | 7/19 | 3174 | 2682 | 5348 | 125 | 39469 | 1192 | 543 |
| | 2002 | 5/7 | 9/30 | 7/4 | 3380 | 2573 | 5347 | 147 | 44105 | 1061 | 426 |
| | 2003 | 5/10 | 9/3 | 7/25 | 2806 | 2601 | 5245 | 117 | 38712 | 743 | 700 |

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

**Table 5-3**: Mean of NDVIz based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date[1] | End date[1] | Peak date[1] | Onset value[2] | End value[2] | Peak value[2] | Length[3] | Time-int.VI[2] | Rt of green up[4] | Rt of sensecence[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 4/28 | 11/4 | 8/25 | 6322 | 4991 | 8681 | 191 | 100698 | 414 | 908 |
| | 2001 | 4/18 | 11/1 | 9/7 | 6432 | 6644 | 8701 | 197 | 98220 | 416 | 851 |
| | 2002 | 5/5 | 11/1 | 8/24 | 2819 | 6341 | 8704 | 180 | 96212 | 860 | 564 |
| | 2003 | 4/4 | 10/24 | 7/26 | 3668 | 5301 | 8716 | 204 | 102581 | 747 | 553 |
| Burnt pine | 2000 | 5/11 | 11/5 | 8/1 | 6649 | 6004 | 8887 | 179 | 100937 | 533 | 515 |
| | 2001 | 3/24 | 10/23 | 7/24 | 5574 | 7237 | 8668 | 214 | 102326 | 559 | 408 |
| | 2002 | 5/1 | 10/17 | 8/20 | 2038 | 6789 | 8618 | 170 | 90511 | 847 | 444 |
| | 2003 | 4/9 | 10/31 | 7/28 | 3080 | 4935 | 8591 | 207 | 97361 | 834 | 582 |
| Cassidy | 2000 | 5/15 | 11/9 | 8/22 | 6773 | 5018 | 9037 | 179 | 104552 | 455 | 785 |
| | 2001 | 5/9 | 10/29 | 8/14 | 6696 | 6937 | 8803 | 173 | 92937 | 478 | 498 |
| | 2002 | 4/18 | 11/3 | 8/15 | 3686 | 6583 | 8904 | 201 | 102274 | 783 | 546 |
| | 2003 | 4/13 | 11/15 | 7/30 | 4631 | 4442 | 8759 | 218 | 106910 | 632 | 579 |
| Chickadee | 2000 | 5/13 | 11/6 | 8/22 | 6048 | 4970 | 8595 | 178 | 93576 | 491 | 769 |
| | 2001 | 4/21 | 11/7 | 8/2 | 5682 | 5660 | 8724 | 201 | 99991 | 662 | 770 |
| | 2002 | 4/28 | 11/6 | 8/20 | 2143 | 5591 | 8391 | 193 | 91066 | 877 | 603 |
| | 2003 | 4/12 | 11/9 | 8/4 | 3126 | 3512 | 8404 | 212 | 97247 | 772 | 775 |
| Fireweed | 2000 | 5/28 | 10/8 | 8/15 | 4598 | 5107 | 7570 | 134 | 64184 | 662 | 654 |
| | 2001 | 4/8 | 10/13 | 8/2 | 4391 | 5245 | 7770 | 189 | 81863 | 536 | 719 |
| | 2002 | 4/19 | 10/6 | 8/14 | 514 | 5876 | 7465 | 170 | 67601 | 738 | 442 |
| | 2003 | 3/31 | 11/24 | 8/2 | 1144 | 1588 | 7633 | 238 | 78272 | 930 | 782 |
| Goose | 2000 | 5/6 | 10/17 | 8/14 | 4035 | 4819 | 7392 | 165 | 73006 | 631 | 623 |
| | 2001 | 4/9 | 10/27 | 8/8 | 3843 | 4437 | 7408 | 202 | 80096 | 557 | 648 |
| | 2002 | 4/24 | 10/18 | 8/14 | 1163 | 5366 | 7480 | 178 | 69885 | 906 | 558 |
| | 2003 | 4/13 | 11/12 | 8/7 | 1641 | 2000 | 7508 | 214 | 77272 | 924 | 838 |
| Kashka | 2000 | 6/11 | 11/12 | 9/5 | 6782 | 4175 | 8329 | 155 | 81691 | 380 | 923 |
| | 2001 | 4/28 | 11/5 | 8/5 | 5790 | 5641 | 8546 | 192 | 96038 | 643 | 1113 |
| | 2002 | 4/22 | 11/13 | 9/3 | 1518 | 5226 | 8144 | 206 | 89225 | 773 | 850 |
| | 2003 | 4/2 | 11/6 | 8/18 | 3271 | 2619 | 8098 | 220 | 96070 | 575 | 1037 |
| Millions | 2000 | 4/18 | 11/12 | 9/6 | 6701 | 4297 | 8509 | 209 | 112731 | 289 | 969 |
| | 2001 | 4/11 | 11/12 | 7/19 | 6629 | 6072 | 9170 | 216 | 116969 | 490 | 670 |
| | 2002 | 4/29 | 11/15 | 9/2 | 3542 | 5773 | 8456 | 200 | 105953 | 760 | 623 |
| | 2003 | 4/13 | 10/28 | 8/19 | 3831 | 4363 | 8396 | 199 | 105438 | 596 | 844 |
| Mosquito | 2000 | 4/24 | 11/16 | 8/20 | 5487 | 4466 | 8606 | 207 | 97030 | 505 | 736 |
| | 2001 | 4/13 | 11/5 | 7/21 | 5282 | 5769 | 8558 | 207 | 95363 | 655 | 462 |
| | 2002 | 4/17 | 11/14 | 8/12 | 2685 | 5276 | 8419 | 212 | 90382 | 844 | 577 |
| | 2003 | 4/5 | 11/19 | 8/15 | 2600 | 3463 | 8552 | 229 | 98281 | 736 | 805 |
| Pierre | 2000 | 5/10 | 11/9 | 9/4 | 5783 | 4432 | 7774 | 184 | 88574 | 365 | 777 |
| | 2001 | 4/18 | 11/5 | 8/24 | 5489 | 5891 | 8294 | 201 | 96539 | 454 | 875 |
| | 2002 | 5/6 | 10/14 | 8/19 | 2112 | 6689 | 8200 | 162 | 81765 | 803 | 421 |
| | 2003 | 4/15 | 11/3 | 8/22 | 4307 | 3247 | 8266 | 203 | 96890 | 491 | 961 |
| Sak A | 2000 | 5/5 | 11/2 | 8/18 | 5443 | 5137 | 8316 | 182 | 90833 | 533 | 673 |
| | 2001 | 4/20 | 11/1 | 8/14 | 5483 | 5513 | 8293 | 196 | 96972 | 498 | 753 |
| | 2002 | 4/29 | 10/31 | 8/21 | 1914 | 5865 | 8296 | 185 | 86539 | 887 | 586 |
| | 2003 | 4/10 | 11/13 | 8/4 | 2386 | 3642 | 8200 | 218 | 92519 | 867 | 690 |
| Sak B | 2000 | 4/19 | 11/5 | 8/7 | 4012 | 5034 | 8571 | 201 | 92828 | 714 | 584 |
| | 2001 | 4/9 | 10/26 | 8/9 | 4107 | 5475 | 8581 | 200 | 91709 | 691 | 951 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 4/3 | 11/8 | 8/8 | 674 | 4313 | 7985 | 220 | 82115 | 981 | 817 |
| | 2003 | 3/19 | 11/23 | 7/24 | 1848 | 2414 | 8151 | 250 | 83469 | 861 | 766 |
| Thistle | 2000 | 4/26 | 11/4 | 8/27 | 5935 | 4555 | 8402 | 193 | 97510 | 438 | 953 |
| | 2001 | 3/30 | 11/5 | 8/22 | 5366 | 5609 | 8281 | 221 | 102849 | 519 | 927 |
| | 2002 | 5/1 | 11/8 | 9/1 | 2337 | 5431 | 8304 | 193 | 90633 | 833 | 732 |
| | 2003 | 3/29 | 11/7 | 8/1 | 2946 | 3829 | 8303 | 224 | 98682 | 752 | 708 |
| Toby | 2000 | 4/27 | 11/5 | 8/2 | 6002 | 5269 | 8538 | 193 | 94571 | 607 | 535 |
| | 2001 | 4/26 | 11/2 | 8/20 | 5876 | 5539 | 8740 | 191 | 102322 | 521 | 933 |
| | 2002 | 5/6 | 10/5 | 8/10 | 2393 | 6821 | 8418 | 152 | 83923 | 925 | 381 |
| | 2003 | 4/4 | 11/6 | 8/5 | 3448 | 2987 | 8394 | 217 | 101200 | 665 | 839 |
| Two creek | 2000 | 5/16 | 11/4 | 8/24 | 6002 | 4971 | 8650 | 172 | 92460 | 504 | 808 |
| | 2001 | 4/7 | 11/4 | 8/15 | 5490 | 5288 | 8516 | 212 | 104114 | 496 | 836 |
| | 2002 | 4/29 | 11/11 | 8/14 | 2111 | 5143 | 8530 | 196 | 91071 | 952 | 587 |
| | 2003 | 4/8 | 11/11 | 8/1 | 3060 | 3603 | 8526 | 218 | 98783 | 811 | 748 |
| Willow | 2000 | 5/9 | 11/3 | 8/15 | 5945 | 5019 | 8632 | 179 | 90722 | 563 | 695 |
| | 2001 | 4/9 | 10/30 | 8/17 | 5225 | 5774 | 8542 | 205 | 99141 | 529 | 732 |
| | 2002 | 4/20 | 11/5 | 8/13 | 2046 | 5591 | 8517 | 200 | 87848 | 946 | 629 |
| | 2003 | 4/1 | 11/17 | 7/27 | 2904 | 3626 | 8563 | 230 | 98434 | 799 | 659 |

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

**Table 5-4**: Mean of NDVIm based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date[1] | End date[1] | Peak date[1] | Onset value[2] | End value[2] | Peak value[2] | Length[3] | Time-int.VI[2] | Rt of green up[4] | Rt of sense-cence[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 5/3 | 11/5 | 8/26 | 6575 | 4460 | 8676 | 188 | 99883 | 400 | 1021 |
| | 2001 | 4/21 | 11/4 | 9/8 | 6462 | 6048 | 8703 | 198 | 103752 | 369 | 1093 |
| | 2002 | 5/11 | 10/27 | 8/24 | 3148 | 6203 | 8682 | 170 | 95421 | 873 | 612 |
| | 2003 | 4/16 | 10/22 | 7/26 | 4277 | 5001 | 8747 | 189 | 99035 | 784 | 587 |
| Burnt pine | 2000 | 5/4 | 11/10 | 8/1 | 6455 | 4426 | 8863 | 191 | 100009 | 572 | 713 |
| | 2001 | 3/25 | 11/2 | 7/31 | 5607 | 6332 | 8702 | 223 | 107817 | 510 | 685 |
| | 2002 | 5/9 | 10/23 | 8/22 | 2784 | 6359 | 8632 | 168 | 92908 | 870 | 510 |
| | 2003 | 4/21 | 10/25 | 7/30 | 3862 | 4641 | 8597 | 188 | 93971 | 825 | 674 |
| Cassidy | 2000 | 5/8 | 11/10 | 8/19 | 6824 | 4313 | 9051 | 187 | 104429 | 418 | 842 |
| | 2001 | 5/11 | 11/5 | 8/14 | 6775 | 5781 | 8821 | 179 | 98388 | 507 | 743 |
| | 2002 | 4/28 | 11/3 | 8/17 | 4270 | 6134 | 8915 | 190 | 100997 | 811 | 628 |
| | 2003 | 4/24 | 11/3 | 7/30 | 5258 | 4481 | 8759 | 194 | 100210 | 642 | 623 |
| Chickadee | 2000 | 5/14 | 11/6 | 8/22 | 6327 | 4326 | 8601 | 177 | 93866 | 486 | 842 |
| | 2001 | 4/24 | 11/7 | 8/3 | 5834 | 4968 | 8749 | 198 | 101097 | 784 | 941 |
| | 2002 | 5/7 | 11/3 | 8/22 | 2593 | 5318 | 8401 | 181 | 91221 | 926 | 697 |
| | 2003 | 4/22 | 11/1 | 8/4 | 3625 | 3408 | 8406 | 194 | 94111 | 804 | 833 |
| Fireweed | 2000 | 6/2 | 10/9 | 8/15 | 4797 | 4787 | 7597 | 130 | 61425 | 735 | 684 |
| | 2001 | 4/7 | 10/12 | 8/2 | 4359 | 4726 | 7788 | 189 | 83690 | 532 | 763 |
| | 2002 | 5/1 | 10/21 | 8/17 | 577 | 5039 | 7459 | 174 | 70312 | 965 | 606 |
| | 2003 | 4/18 | 11/11 | 8/2 | 2722 | 1501 | 7633 | 208 | 76289 | 916 | 859 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Goose | 2000 | 5/11 | 10/16 | 8/14 | 4242 | 4493 | 7403 | 159 | 71874 | 677 | 665 |
| | 2001 | 4/9 | 10/22 | 8/8 | 3672 | 4184 | 7405 | 196 | 79851 | 587 | 715 |
| | 2002 | 5/6 | 10/22 | 8/16 | 1496 | 4849 | 7471 | 170 | 71055 | 1036 | 667 |
| | 2003 | 4/27 | 11/3 | 8/8 | 2827 | 1909 | 7511 | 191 | 75862 | 886 | 895 |
| Kashka | 2000 | 6/3 | 11/10 | 8/31 | 6630 | 3893 | 8335 | 160 | 82103 | 415 | 901 |
| | 2001 | 4/27 | 11/4 | 8/14 | 5844 | 5138 | 8641 | 192 | 96812 | 760 | 1495 |
| | 2002 | 5/2 | 11/10 | 9/4 | 1857 | 4998 | 8162 | 193 | 90887 | 824 | 915 |
| | 2003 | 4/14 | 10/31 | 8/18 | 3628 | 2548 | 8098 | 201 | 92555 | 603 | 1077 |
| Millions | 2000 | 4/19 | 11/9 | 9/5 | 7517 | 4129 | 8525 | 205 | 113467 | 186 | 956 |
| | 2001 | 4/13 | 11/10 | 7/19 | 6773 | 5807 | 9179 | 213 | 117349 | 517 | 695 |
| | 2002 | 5/3 | 11/11 | 9/3 | 3922 | 5682 | 8457 | 193 | 105887 | 668 | 643 |
| | 2003 | 4/21 | 10/25 | 8/19 | 4219 | 4363 | 8396 | 188 | 102573 | 596 | 847 |
| Mosquito | 2000 | 4/27 | 11/10 | 8/19 | 5588 | 3940 | 8610 | 198 | 97383 | 533 | 807 |
| | 2001 | 4/18 | 11/4 | 7/27 | 5234 | 4816 | 8590 | 202 | 96115 | 638 | 612 |
| | 2002 | 4/27 | 11/11 | 8/14 | 3435 | 4687 | 8430 | 199 | 92450 | 823 | 656 |
| | 2003 | 4/17 | 11/7 | 8/15 | 2960 | 3345 | 8552 | 206 | 95296 | 783 | 886 |
| Pierre | 2000 | 5/10 | 11/7 | 9/3 | 5910 | 4230 | 7831 | 182 | 89626 | 377 | 833 |
| | 2001 | 4/18 | 11/4 | 8/28 | 5473 | 5693 | 8277 | 201 | 97883 | 502 | 1059 |
| | 2002 | 5/14 | 10/11 | 8/19 | 2736 | 6584 | 8196 | 150 | 79068 | 877 | 461 |
| | 2003 | 4/27 | 10/29 | 8/23 | 4871 | 3112 | 8266 | 187 | 92725 | 479 | 1000 |
| Sak A | 2000 | 5/6 | 11/2 | 8/18 | 5575 | 4366 | 8320 | 181 | 91003 | 558 | 766 |
| | 2001 | 4/22 | 11/2 | 8/15 | 5533 | 4892 | 8299 | 195 | 97239 | 533 | 892 |
| | 2002 | 5/8 | 10/29 | 8/23 | 2272 | 5529 | 8284 | 176 | 87234 | 955 | 677 |
| | 2003 | 4/22 | 11/5 | 8/5 | 3278 | 3391 | 8210 | 197 | 90087 | 858 | 768 |
| Sak B | 2000 | 5/1 | 11/5 | 8/8 | 4508 | 4108 | 8565 | 189 | 91171 | 758 | 701 |
| | 2001 | 4/14 | 10/24 | 8/9 | 4100 | 5040 | 8526 | 194 | 89394 | 754 | 1056 |
| | 2002 | 4/21 | 11/5 | 8/9 | 1158 | 3768 | 7974 | 199 | 81974 | 1092 | 901 |
| | 2003 | 4/7 | 11/10 | 7/24 | 2101 | 1620 | 8151 | 219 | 81599 | 998 | 895 |
| Thistle | 2000 | 4/28 | 11/3 | 8/27 | 6274 | 4042 | 8403 | 190 | 98494 | 426 | 1023 |
| | 2001 | 4/1 | 11/6 | 8/27 | 5363 | 4984 | 8307 | 220 | 106160 | 539 | 1161 |
| | 2002 | 5/8 | 11/6 | 9/2 | 2675 | 5096 | 8329 | 183 | 91292 | 872 | 816 |
| | 2003 | 4/11 | 10/30 | 8/1 | 3379 | 3766 | 8303 | 203 | 95298 | 829 | 741 |
| Toby | 2000 | 4/27 | 11/9 | 8/1 | 6118 | 4417 | 8566 | 197 | 99081 | 711 | 643 |
| | 2001 | 4/30 | 11/3 | 8/22 | 5934 | 5211 | 8738 | 189 | 101083 | 648 | 1059 |
| | 2002 | 5/14 | 10/3 | 8/10 | 2948 | 6697 | 8446 | 143 | 82924 | 946 | 398 |
| | 2003 | 4/17 | 10/31 | 8/5 | 4224 | 2987 | 8394 | 198 | 97207 | 649 | 850 |
| Two creek | 2000 | 5/18 | 11/4 | 8/24 | 6192 | 4150 | 8652 | 171 | 91665 | 509 | 926 |
| | 2001 | 4/10 | 11/6 | 8/17 | 5535 | 4379 | 8532 | 210 | 104860 | 515 | 1053 |
| | 2002 | 5/8 | 11/5 | 8/14 | 2435 | 4865 | 8533 | 182 | 90721 | 1026 | 646 |
| | 2003 | 4/20 | 11/2 | 8/1 | 3779 | 3462 | 8525 | 197 | 94966 | 825 | 800 |
| Willow | 2000 | 5/5 | 11/4 | 8/11 | 5929 | 3984 | 8680 | 184 | 92394 | 572 | 796 |
| | 2001 | 4/11 | 11/4 | 8/19 | 5257 | 4741 | 8553 | 208 | 100217 | 533 | 941 |
| | 2002 | 5/1 | 11/5 | 8/14 | 2515 | 5033 | 8545 | 188 | 89673 | 1062 | 718 |
| | 2003 | 4/16 | 11/5 | 7/27 | 3476 | 3522 | 8555 | 204 | 93655 | 857 | 724 |

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

**Table 5-5**: Mean, standard deviation and ANOVA p-values for the four comparative approaches.

| VPMs | Year | Four comparative approaches | | | | | | | | ANOVA p-value |
|---|---|---|---|---|---|---|---|---|---|---|
| | | M1 (EVIm) | | M2 (NDVIm) | | M3 (EVIz) | | M4 (NDVIz) | | |
| | | Mean | St_dev | Mean | St_dev | Mean | St_dev | Mean | St_dev | |
| Onset date | 2000 | 148.6 | 10.0 | 129.6 | 12.3 | 142.0 | 10.9 | 128.8 | 14.2 | < 0.001 |
| | 2001 | 144.7 | 6.4 | 107.7 | 11.5 | 138.6 | 8.3 | 105.8 | 11.5 | < 0.001 |
| | 2002 | 126.7 | 7.9 | 126.4 | 6.3 | 122.1 | 7.1 | 117.0 | 8.6 | < 0.001 |
| | 2003 | 132.8 | 7.4 | 110.3 | 5.5 | 127.2 | 8.1 | 97.5 | 7.2 | < 0.001 |
| End date | 2000 | 261.1 | 8.5 | 309.0 | 9.1 | 266.5 | 10.4 | 309.2 | 9.6 | < 0.001 |
| | 2001 | 256.8 | 12.6 | 307.1 | 7.4 | 265.2 | 12.0 | 306.0 | 7.0 | < 0.001 |
| | 2002 | 262.6 | 14.5 | 304.1 | 11.3 | 268.7 | 14.9 | 304.7 | 13.9 | < 0.001 |
| | 2003 | 248.1 | 9.3 | 306.8 | 5.6 | 252.7 | 9.8 | 315.3 | 8.7 | < 0.001 |
| Peak date | 2000 | 208.7 | 9.0 | 232.6 | 10.6 | 207.8 | 9.3 | 233.5 | 11.0 | < 0.001 |
| | 2001 | 200.8 | 11.6 | 226.1 | 13.2 | 200.5 | 11.4 | 223.4 | 13.3 | < 0.001 |
| | 2002 | 193.1 | 10.6 | 233.7 | 8.2 | 191.6 | 12.2 | 232.4 | 8.2 | < 0.001 |
| | 2003 | 199.0 | 8.6 | 218.5 | 9.0 | 197.8 | 8.7 | 218.2 | 9.0 | < 0.001 |
| Onset value | 2000 | 2978.6 | 269.6 | 5966.3 | 866.3 | 2722.1 | 249.1 | 5782.3 | 889.8 | < 0.001 |
| | 2001 | 3156.5 | 314.0 | 5484.7 | 870.0 | 2882.8 | 321.8 | 5459.7 | 811.1 | < 0.001 |
| | 2002 | 3098.6 | 362.8 | 2551.3 | 957.8 | 2828.9 | 367.5 | 2105.9 | 871.9 | < 0.001 |
| | 2003 | 2724.1 | 316.1 | 3655.4 | 810.0 | 2411.4 | 366.2 | 2993.2 | 930.0 | < 0.001 |
| End value | 2000 | 3006.2 | 290.1 | 4254.0 | 238.9 | 3003.8 | 298.5 | 4891.5 | 442.7 | < 0.001 |
| | 2001 | 2765.0 | 237.8 | 5171.3 | 602.8 | 2727.4 | 227.8 | 5795.7 | 679.2 | < 0.001 |
| | 2002 | 2672.6 | 191.4 | 5427.6 | 798.3 | 2686.1 | 208.7 | 5792.1 | 701.7 | < 0.001 |
| | 2003 | 2649.9 | 225.5 | 3316.1 | 1039.9 | 2665.6 | 216.0 | 3473.2 | 1008.9 | < 0.001 |
| Peak value | 2000 | 5185.1 | 544.5 | 8417.4 | 445.7 | 5207.8 | 553.4 | 8405.6 | 453.7 | < 0.001 |
| | 2001 | 5054.5 | 455.4 | 8488.1 | 418.6 | 5063.4 | 453.2 | 8474.7 | 414.7 | < 0.001 |
| | 2002 | 4890.9 | 386.5 | 8307.3 | 396.0 | 4909.8 | 384.8 | 8301.9 | 391.0 | < 0.001 |
| | 2003 | 4907.0 | 350.4 | 8318.9 | 350.3 | 4911.6 | 345.8 | 8316.3 | 348.6 | < 0.001 |
| Length | 2000 | 113.6 | 13.6 | 180.6 | 18.4 | 125.4 | 16.4 | 181.3 | 19.1 | < 0.001 |
| | 2001 | 113.1 | 14.6 | 200.4 | 11.8 | 127.6 | 14.7 | 201.1 | 11.9 | < 0.001 |
| | 2002 | 136.9 | 17.2 | 178.7 | 16.1 | 147.6 | 17.3 | 188.6 | 18.8 | < 0.001 |
| | 2003 | 116.4 | 13.2 | 197.8 | 8.8 | 126.4 | 15.2 | 218.8 | 13.4 | < 0.001 |
| Time-int. VI | 2000 | 37535 | 5193 | 92367 | 12408 | 40326 | 5889 | 92243 | 11727 | < 0.001 |
| | 2001 | 35911 | 4107 | 98856 | 9105 | 38784 | 4189 | 97340 | 8628 | < 0.001 |
| | 2002 | 39276 | 5143 | 88376 | 9549 | 40857 | 5359 | 87937 | 9896 | < 0.001 |
| | 2003 | 35439 | 3015 | 92214 | 7817 | 36804 | 2896 | 95588 | 8718 | < 0.001 |
| Rt of greenup | 2000 | 873.4 | 182.2 | 520.8 | 152.5 | 691.8 | 134.7 | 505.3 | 114.6 | < 0.001 |
| | 2001 | 977.1 | 374.7 | 576.8 | 112.4 | 715.1 | 211.2 | 544.0 | 79.9 | < 0.001 |
| | 2002 | 826.6 | 123.4 | 914.1 | 109.8 | 701.2 | 84.3 | 857.2 | 73.3 | < 0.001 |
| | 2003 | 798.1 | 189.0 | 770.9 | 138.3 | 737.1 | 162.0 | 749.5 | 127.8 | < 0.001 |
| Rt of senescence | 2000 | 572.7 | 87.9 | 819.9 | 121.7 | 542.0 | 86.2 | 744.2 | 144.4 | < 0.001 |
| | 2001 | 538.1 | 92.8 | 935.2 | 229.5 | 490.6 | 63.0 | 759.1 | 191.6 | < 0.001 |
| | 2002 | 428.0 | 64.8 | 659.4 | 139.0 | 407.9 | 58.6 | 585.0 | 131.9 | < 0.001 |
| | 2003 | 565.8 | 90.0 | 816.2 | 129.1 | 541.6 | 87.0 | 760.4 | 132.8 | < 0.001 |

**Table 5- 6**: Homogenous subsets of VPMs based on Tukey HSD multiple comparison test.

| VPMs | Year | Subset 1 | p-value | Subset 2 | p-value | Subset 3 | p-value |
|---|---|---|---|---|---|---|---|
| Onset date | 2000 | M1, M3 | 0.412 | M2, M4 | 0.998 | | |
| | 2001 | M1, M3 | 0.942 | M2, M4 | 0.291 | | |
| | 2002 | M1, M3 | 0.238 | M1, M2, M4 | 0.317 | | |
| | 2003 | M1, M3 | 0.13 | M2 | 1 | M4 | 1 |
| End date | 2000 | M1, M3 | 0.382 | M2, M4 | 1 | | |
| | 2001 | M1, M3 | 0.096 | M2, M4 | 0.988 | | |
| | 2002 | M1, M3 | 0.592 | M2, M4 | 0.999 | | |
| | 2003 | M1, M3 | 0.433 | M2 | 1 | M4 | 1 |
| Peak date | 2000 | M1, M3 | 0.994 | M2, M4 | 0.995 | | |
| | 2001 | M1, M3 | 1 | M2, M4 | 0.93 | | |
| | 2002 | M1, M3 | 0.977 | M2, M4 | 0.981 | | |
| | 2003 | M1, M3 | 0.981 | M2, M4 | 1 | | |
| Onset value | 2000 | M1, M3 | 0.678 | M2, M4 | 0.852 | | |
| | 2001 | M1, M3 | 0.618 | M2, M4 | 1 | | |
| | 2002 | M1, M3 | 0.129 | M2, M4 | 0.28 | | |
| | 2003 | M1, M3, M4 | 0.073 | M2 | 1 | | |
| End value | 2000 | M1, M3 | 1 | M2 | 1 | M4 | 1 |
| | 2001 | M1, M3 | 0.996 | M2 | 1 | M4 | 1 |
| | 2002 | M1, M3 | 1 | M2, M4 | 0.25 | | |
| | 2003 | M1, M2, M3 | 0.063 | M4 | 1 | | |
| Peak value | 2000 | M1, M3 | 0.999 | M2, M4 | 1 | | |
| | 2001 | M1, M3 | 1 | M2, M4 | 1 | | |
| | 2002 | M1, M3 | 0.999 | M2, M4 | 1 | | |
| | 2003 | M1, M3 | 1 | M2, M4 | 1 | | |
| Length | 2000 | M1, M3 | 0.214 | M2, M4 | 0.999 | | |
| | 2001 | M1 | 1 | M2, M4 | 0.999 | M3 | 1 |
| | 2002 | M1, M3 | 0.312 | M2, M4 | 0.376 | | |
| | 2003 | M1, M3 | 0.134 | M2 | 1 | M4 | 1 |
| Time-integrated VI | 2000 | M1, M3 | 0.835 | M2, M4 | 1 | | |
| | 2001 | M1, M3 | 0.646 | M2, M4 | 0.926 | | |
| | 2002 | M1, M3 | 0.94 | M2, M4 | 0.999 | | |
| | 2003 | M1, M3 | 0.925 | M2, M4 | 0.424 | | |
| Rate of greenup | 2000 | M1 | 1 | M2, M4 | 0.991 | M3 | 1 |
| | 2001 | M1 | 1 | M2, M3, M4 | 0.152 | | |
| | 2002 | M1, M2, M4 | 0.073 | M3 | 1 | | |
| | 2003 | M1, M2, M3, M4 | 0.688 | | | | |
| Rate of senescence | 2000 | M1, M3 | 0.868 | M2, M4 | 0.239 | | |
| | 2001 | M1, M3 | 0.834 | M2 | 1 | M4 | 1 |
| | 2002 | M1, M3 | 0.949 | M2, M4 | 0.2 | | |
| | 2003 | M1, M3 | 0.927 | M2, M4 | 0.497 | | |

N = 16, M1 = EVIm, M2 = NDVIm, M3 = EVIz, M4 = NDVIz

## 5.1 Comparison of Four Approaches Used to Derive VPMs

Methodologies employed by researchers for detecting phenological transition dates from the satellite VI data (see Literature Review II) are somewhat arbitrary (White et al. 1997) and may yield significantly different results. Therefore, the phenological information provided by the four approaches needs to be investigated and compared. Results then must be interpreted and discussed in the specific context of the method used.

### 5.1.1 Zhang versus Zhang modified approach

In general, the OG date derived from the Zhang modified approach tends to occur slightly later than Zhang approach, while the EG date occurs slightly earlier. This results in a shorter length of growing season for the Zhang modified approach. However, there are a few exceptions to this general trend in NDVI VPMs. The length of the growing season is, in fact, longer in the modified approach for the year 2001 for the 1A, Burnt pine, Cassidy, Fireweed, Pierre and Thistle watersheds. Visual observation of the Table 5-1, 5-2, 5-3 and 5-4 reveals that overall the difference between VIm (EVIm and NDVIm) and VIz (EVIz and NDVIz) VPMs is not substantial. The maximum difference for EVI based OG and EG dates is 15 and 12 days, respectively, and for NDVI based OG and EG dates it is 19 and 15 days, respectively. The maximum EVI based OG date and EG date difference in the two approaches is for the Fireweed watershed in 2003 and Cassidy watershed in 2001, respectively and the NDVI based maximum OG date and EG date difference is for Sak B in year 2003 and for Fireweed in year 2002, respectively. These watershed level differences in OG and EG dates for the two approaches can be attributed to random error and data temporal resolution limitations.

Both of the approaches yield almost the same peak date and peak VI value for both the EVI and NDVI. Almost 3 to 10 times greater differences can be seen between the two approaches for the NDVI based OG VI value, EG VI value and time integrated VI value when compared to EVI based values because of the higher NDVI amplitude as compared to the EVI. A higher rate of greenup and senescence for Zhang modified approach was observed compared to Zhang approach with few exceptions in the NDVI based rate metrics. The most notable difference of 661 for greenup and 186 for senescence rates in the two EVI based approaches were seen for the Cassidy watershed in 2001.

The above visual observations are supported by Tukey HSD MCT results in Table 5-6. EVIm and EVIz (M1 and M3) derived VPMs are grouped together in the homogenous subset 1 for almost all of the VPMs in the four years. The exceptions to this trend are for the length of growing season metric in 2001 and the rate of greenup metric in 2000, 2001 and 2002. Likewise, NDVIm and NDVIz (M2 and M4) VPMs are coupled together in homogenous subset 2 most of the time. The instances when NDVIm and NDVIz derived VPMs are different are the OG date in 2003, EG date in 2003, OG value in 2003, EG value in 2000, 2001 and 2003, rate of greenup in 2002 and rate of senescence in 2001. A pattern can be identified by these exceptions: the Zhang method and Zhang modified method yield significantly different VPMs for 2003 MODIS NDVI data. This implies that 2003 MODIS NDVI data is sensitive to both the Zhang and Zhang modified approach in contrast to MODIS 2000, 2001 and 2002 NDVI and the four year MODIS EVI data. This is also supported by the fact that the time integrated VI metric has the lowest p-value for the M2, M4 pair in 2003. Increasing p-values in Table 5-6 above the alpha level of 0.05 reflect the degree of insignificance between class (M1, M2, M3 and M4) differences (p-value > 0.05 implies insignificant differences). EVI and NDVI based peak date and VI value and time integrated VI value are the most perfectly grouped metrics for both of the approaches. It is important to note that for the peak date metric, a difference of less than 16 days implies no significant difference because 16 is the minimum temporal resolution of the data.

### 5.1.2 EVI versus NDVI algorithm

VPMs derived from EVI and NDVI are quite different among the four years. NDVI identifies a very early OG date in April and a delayed EG date in November when compared to the EVI based OG date in May and EG date in September. All VPMs for the four years differ for NDVI and EVI except for the OG date metric in 2002 when M1, M3, and M4 are grouped together; the OG value metric in 2003 when M1, M3, and M4 are grouped together; and EG value metric in 2003 when M1, M2, and M3 are grouped together in the same homogenous subset (see Table 5-6). The rate of greenup metric exhibits the most serious deviation from the observed trend since M2, M3, M4 for year 2001; M1, M3, M4 for the year 2002; and M1, M2, M3, M4 for the year 2003 are coupled together in the same homogenous subset. These exceptions can be partly attributed to already observed unique behavior of 2003 NDVI data, which yields significantly different VPMs for the Zhang and Zhang modified approaches. The result is the random coupling of M2 (NDVIm) and M4 (NDVIz) with M1 (EVIm) and M3 (EVIz) in the same homogenous subset.

To investigate further into the different responses of MODIS NDVI versus EVI, to extract VPMs, the Pearson correlation coefficient between raw and treated EVI and NDVI for each pixel (including all 23 composite periods) was first computed and then spatially averaged over each watershed for each year. A weak correlation between NDVI and EVI can be seen in Table 5-7.

**Table 5-7**: Mean of Pearson correlation coefficients between per-pixel NDVI and EVI for 2000 to 2003.

| Watersheds | Raw data | | | | Treated data | | | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | 2001 | 2002 | 2003 | 2000 | 2001 | 2002 | 2003 |
| 1A | 0.51 | 0.37 | 0.54 | 0.51 | 0.47 | 0.43 | 0.46 | 0.48 |
| Burnt pine | 0.53 | 0.46 | 0.56 | 0.55 | 0.66 | 0.67 | 0.57 | 0.63 |
| Cassidy | 0.49 | 0.37 | 0.49 | 0.68 | 0.55 | 0.47 | 0.50 | 0.55 |
| Chickadee | 0.51 | 0.39 | 0.54 | 0.49 | 0.53 | 0.49 | 0.49 | 0.45 |
| Fireweed | 0.59 | 0.54 | 0.63 | 0.64 | 0.62 | 0.62 | 0.55 | 0.50 |
| Goose | 0.67 | 0.66 | 0.67 | 0.69 | 0.63 | 0.62 | 0.58 | 0.56 |
| Kashka | 0.43 | 0.34 | 0.42 | 0.48 | 0.36 | 0.45 | 0.27 | 0.28 |
| Millions | 0.30 | 0.14 | 0.33 | 0.23 | 0.38 | 0.27 | 0.27 | 0.07 |
| Mosquito | 0.62 | 0.54 | 0.56 | 0.60 | 0.66 | 0.66 | 0.58 | 0.57 |
| Pierre | 0.41 | 0.35 | 0.52 | 0.34 | 0.49 | 0.45 | 0.34 | 0.38 |
| Sak A | 0.55 | 0.45 | 0.54 | 0.61 | 0.61 | 0.54 | 0.50 | 0.55 |
| Sak B | 0.78 | 0.71 | 0.71 | 0.80 | 0.74 | 0.79 | 0.61 | 0.66 |
| Thistle | 0.34 | 0.32 | 0.50 | 0.46 | 0.28 | 0.31 | 0.48 | 0.30 |
| Toby | 0.41 | 0.37 | 0.44 | 0.30 | 0.51 | 0.47 | 0.28 | 0.37 |
| Two creek | 0.56 | 0.45 | 0.60 | 0.57 | 0.56 | 0.45 | 0.56 | 0.52 |
| Willow | 0.56 | 0.47 | 0.58 | 0.59 | 0.58 | 0.59 | 0.55 | 0.54 |
| All area | 0.57 | 0.48 | 0.58 | 0.59 | 0.58 | 0.53 | 0.52 | 0.52 |

The effect of data treatment on the correlation coefficient was mixed. In some cases it improved the coefficient by as much as 0.22 while in other cases it reduced the coefficient by as much as 0.18. Moreover, visual analysis of a large number of pixels revealed that the big modes in the vegetation growth cycles frequently did not line up between NDVI and EVI. In theory, the indices should be very highly correlated: timings of major changes of the two VI methods should differ very slightly with scale differences serving as the primary distinction. Comparisons made at the Kansas Applied Remote Sensing Laboratory revealed that the correlation coefficients were almost always greater than 0.9 (Kastens 2004, verbal communication).

MODIS' "Known Product Issues" website (LDOPE 2004) has also acknowledged the inconsistent NDVI versus EVI values under certain conditions in collection 4 VI data (Case #: DR_MOD13_01274; Opening date: October 1 2001; Last updated: September 6 2004; Status: Pending). NDVI and EVI values were significantly uncorrelated for the Okavango Delta in Botswana, with the scatter plot indicating a strong land cover dependency of the effect.

The early prediction of NDVI based OG date and NDVI's weak correlation to the EVI data can be attributed to the way the NDVI algorithm is designed (see Literature Review I under MODIS NDVI). The enhanced sensitivity of the NDVI algorithm over low biomass regions is achieved at the expense of reduced sensitivity at the high biomass regions, resulting in the NDVI saturation problems. The EVI, being a non-ratio index, responds more linearly to the variations in high biomass regions. It was found to perform well in the heavy aerosol, biomass burning conditions in Brazil (Miura et al. 1998).

Theoretically, the EVI algorithm is expected to perform better than the NDVI to monitor vegetation dynamics for the FORWARD study area because of the open canopy. Such canopies have significant background contamination that adversely impacts the canopy's reflectance properties (Graetz 1990). The EVI isolates the green photosynthetically active reflectance signal from the spatially and temporally variable background effect, only taking the upper-storey (forest canopy) reflected radiations into account, to allow for more meaningful inter-comparisons. On the other hand, NDVI variations are induced by canopy background contamination that includes soils, leaf litter, water, and weathered geologic substrates such as peat, moss, etc. However, one major factor contributing to the weak correlation of NDVI versus EVI for the FORWARD study area is the presence of snow during the winter months. While NDVI algorithm exhibits extremely low values, the EVI algorithm results in abnormally high values for the snow because it employs the blue reflectance term that for snow is higher than the green, red and NIR reflectances (see Figure 2-1 Literature Review-I section). NDVI values for snow are either zero or negative since snow has higher red than the NIR reflectance. This reasoning is further supported below (see section 5.4 Environmental Control of Vegetation Phenology) and was also confirmed by the improved correlation coefficient (0.7 to 0.9) when the winter NDVI and EVI (or snow NDVI and EVI) values were removed from the correlation coefficient computation.

The FORWARD study area, covered with snow in the months of March and April, is an important consideration regarding the OG date detection. Average snow depth recorded by Environment Canada's weather station at the Whitecourt airport location in Alberta (54° 8'-N 115° 47'-W, Elevation: 782.4 m) from 1971 to 2000, was 22, 25, 18 and 3 cm (median values were 22, 25, 18 and 1 cm) in January, February, March and April (Environment Canada 2004*c*). The highest snow depth of 700 mm was recorded in 1982 for the month of April (Environment Canada 2004*c*). Moreover, snow depth recorded for the period 1971 to 2000, at the end of April is zero (Environment Canada 2004*c*), which indicates that snowmelt always occurred before the end of April. Daily snow depth values for the period of 2000 to 2003 were also checked at Environment Canada's website for the Whitecourt weather station and it was confirmed that a trace amount of snow was found on the ground in the month of April and even in May. The VPM extraction algorithm employed in this study identifies the point of inflection, when the NDVI time-series curve exhibits the greatest increase in amplitude as the OG date. It appears that the OG point for the NDVI time-series data does not correspond to the canopy OG but represents the snow melt event, when the bare ground vegetation (shrubs, herbs, grass, and a thick organic layer) starts to show up and drastically increase NDVI values. The sudden jump in the NDVI amplitude is tagged as OG by the VPM extraction algorithm. This reasoning is consistent with statements by Schwartz and Reed (1999), who concluded that the consistent early OG dates were actually under-storey greenup rather than canopy greenup dates, while using the AVHRR NDVI data to derive the OG and EG dates. Figure 5-2 and 5-3 depict a comparison of EVI versus NDVI data behavior for the Sak A watershed for all four years (2000 to 2003) and for the year 2001, respectively.

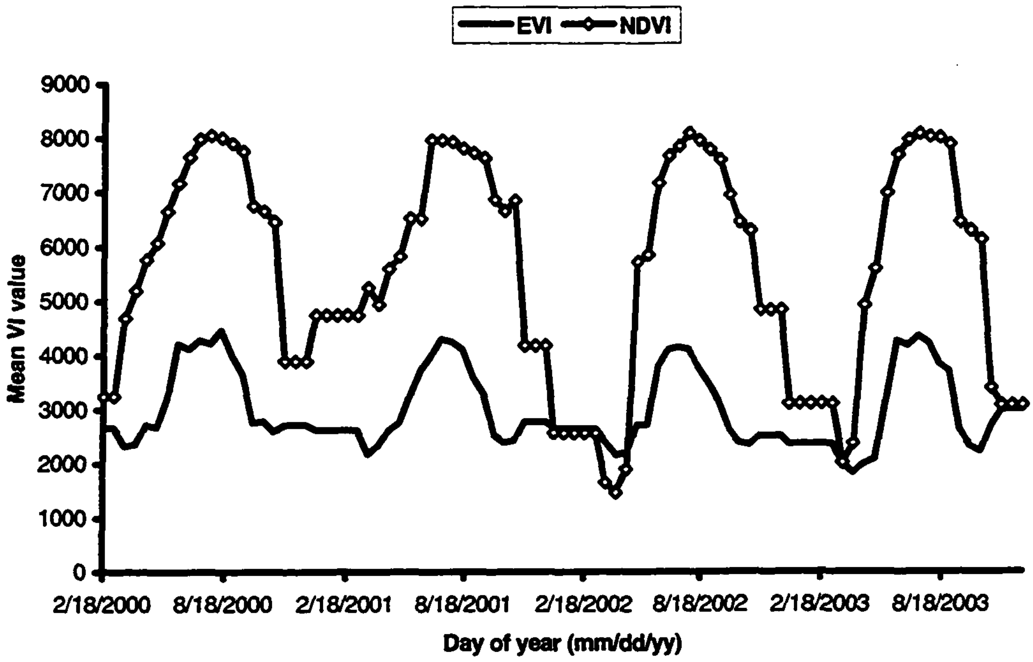


**Figure 5-2:** Comparison of time-series treated EVI versus NDVI for the Sak A watershed.

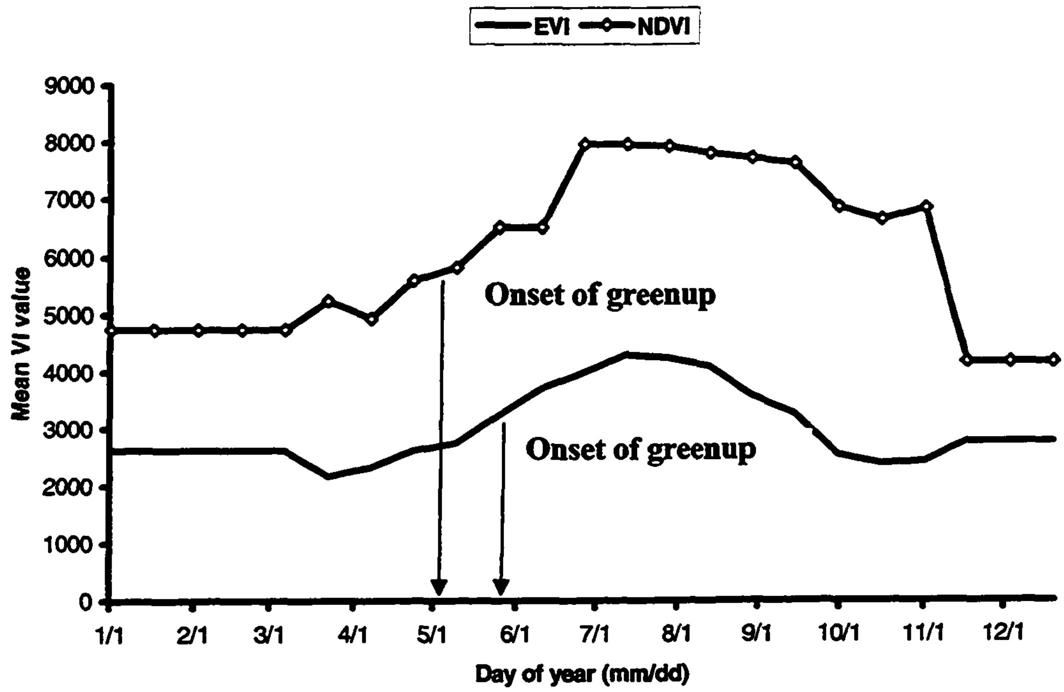


**Figure 5-3:** Comparison of 2001 treated EVI versus NDVI data for Sak A watershed.

## 5.2 Assess the Validity of VPMs

Validity of the VPMs was checked by examining the coincidence between satellite derived OG dates and actual ground based first bloom, full bloom, and leaf out event dates. Beaubien (2001) has compiled and reported first and full bloom dates for various indicator species in Alberta and the Northwest Territories (NWT) through the Plantwatch program (see Literature Review II section under Phenology) for the year 2001 (see Table 5-9). These phenological observations are based on the criteria set by the Plantwatch program protocols and are reproduced from the Plantwatch website (Beaubien 2003) as Table 5-8.

**Table 5-8**: Criteria for observing the first and full bloom dates of different plant species.

| Species | First bloom | Full bloom |
|---|---|---|
| Aspen poplar | Half the catkins on the tree had started to shed pollen | Most of the catkins have turned pale yellow |
| Prairie crocus | At least two to five flowers have opened in a crocus patch, revealing the yellow stamens | Most blooms are open – not many new buds are left |
| Serviceberry | At least 50% of the flower clusters have at least one open flower | About 90% of the flower clusters no longer have any unopened flowers |
| Common purple lilac | At least 50% of the flower clusters had at least one open flower | About 95% of the flower clusters no longer had any unopened flowers but before many of the flowers have withered or dried up |
| Tamarack | The first pollen from male cones is being shed, in at least three different places | Half of the male cones are abundantly shedding pollen |
| Tamarack (leaf out event) | When, in at least three places on tree, the tuft of needles, after considerable lengthening, starts loosening up and spreading at the tip | |

Aspen poplar (*Populus tremuloides*) is the major hardwood tree species in the western Canadian Boreal Forest and parkland and is by far the most abundant species (Peterson and Peterson 1992; Hogg 1994). It is the earliest flowering species in the growing season when compared to other native species such as serviceberry (*Amelanchier alnifolia*) and choke cherry (*Prunus virginiana*), and has a sharp first flowering (Beaubien and Freeland 2000). It produces flowers on an average of one month before the last killing frost (Lechowicz 1995) when spring temperatures above 12 °C last for a duration of 6 days (Perala 1990). Bud development depends on the air temperature at the height of the buds (Lechowicz 1984). The earlier flowering species show more inter-annual variability in the bloom time as compared to later flowering species (Fitter et al. 1995). Hence, phenology of aspen poplar can be a sensitive indicator of climatic changes. Beaubien and Freeland (2000) studied the first-bloom dates for Aspen poplar in Edmonton, Alberta from a 20 year historical dataset and reported the mean first flowering date as April 13.

**Table 5-9**: Bloom dates for different indicator species in Alberta and NWT for the year 2001.

| Species | Type | City, Province | First bloom | Full bloom | LAT-North | LONG-West |
|---|---|---|---|---|---|---|
| Aspen Poplar | Deciduous | Hay River, NWT | May 10 | May 12 | 60.8234 | 115.7796 |
| Aspen Poplar | Deciduous | Hay River, NWT | May 25* | May 28** | 60.8234 | 115.7796 |
| Aspen Poplar | Deciduous | Hay River, NWT | | May 29** | 60.8234 | 115.7796 |
| Aspen Poplar | Deciduous | Near Lac La Biche, AB | May 12 | | 54.7333 | 113.1031 |
| Aspen Poplar | Deciduous | Devonian Botanic Garden, AB | | April 17 | 53.46 | 113.83 |
| Aspen Poplar | Deciduous | Devonian Botanic Garden, AB | May 2* | May 4** | 53.46 | 113.83 |
| Aspen Poplar | Deciduous | St. Paul, AB | April 17 | April 27 | 53.9017 | 111.1681 |
| Aspen Poplar | Deciduous | St. Paul, AB | April 30* | May 4** | 53.9017 | 111.1681 |
| Aspen Poplar | Deciduous | Cochrane, AB | May 18* | May 22** | 51.28 | 114.68 |
| Aspen Poplar | Deciduous | Sylvan Lake, AB | May 12* | May 14** | 52 | 114 |
| Service berry | Deciduous shrub | Devonian Botanic Garden, AB | May 18 | May 21 | 53.46 | 113.83 |
| Service berry | Deciduous shrub | Devonian Botanic Garden, AB | May 20 | May 22 | 53.46 | 113.83 |
| Service berry | Deciduous shrub | Devonian Botanic Garden, AB | | May 24 | 53.46 | 113.83 |
| Service berry | Deciduous shrub | St. Paul, AB | | May 27 | 53.9017 | 111.1681 |
| Purple lilac | Deciduous | Legal, AB | May 21 | May 25 | 53.95 | 113.88 |
| Purple lilac | Deciduous | Beaumont, AB | May 24 | May 31 | 53.5 | 113.4167 |
| Purple lilac | Deciduous | St. Paul, AB | May 26 | June 3 | 53.9017 | 111.1681 |
| Purple lilac | Deciduous | Devonian Botanic Garden, AB | May 25 | | 53.46 | 113.83 |
| Purple lilac | Deciduous | Fort McMurray, AB | May 28 | June 3 | 56 | 111 |
| Purple lilac | Deciduous | Hay River, NWT | June 12 | June 19 | 60.8234 | 115.7796 |
| Prairie crocus | Conifer shrub | Near Lac La Biche, AB | | April 28 | 54.9608 | 112.4433 |
| Prairie crocus | Conifer shrub | Sandy Lake, AB | | May 20 | 60.5167 | 114.5833 |
| Tamarack | Deciduous | Yellowknife, NWT | May 31 | | 62.45 | 114.35 |
| Tamarack | Deciduous | Yellowknife, NWT | June 2 (Leaf out) | | 62.45 | 114.35 |

* Leaves dime size
** Leaves quarter size

Dates marked with asterisk (*) and double asterisk (**), instead of first or full bloom, indicate the time when the leaves are of dime size and quarter size, respectively. First and full bloom date points towards the flowering, which, for these indicator species, often occurs before the leaves are fully developed. Satellite detected OG and EG are related to the level of photosynthetic activity in the ecosystem that neither strictly conceptualizes the exact ground based phenology events nor is consistent with budburst, first or full bloom, leaves dime size or leaves quarter size (for the OG event) and actual dormancy condition (for the EG event). However, satellite derived OG have been reported to occur after the initial leaf expansion and EG to coincide with a 15 to 50% leaf fall event (White et al. 1997).

Table 5-10 presents 16 FORWARD watershed's land cover composition as a percentage of each watershed area.

**Table 5-10:** FORWARD watersheds' land cover composition.

| | | Land cover unit (% watershed area) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Watersheds | Area ($km^2$) | Deciduous | Coniferous | Mixed woods | Range land | Peat lands | Urban industry & roads |
| Large burnt | Goose | 150.57 | 13.97 | 65.72 | 7.83 | 4.13 | 7.86 | 0.48 |
| | Sak A | 233.93 | 2.81 | 72.61 | 5.18 | 9.68 | 9.21 | 0.47 |
| Large unburnt | Chickadee | 155.19 | 27.15 | 32.38 | 14.90 | 3.65 | 20.89 | 1.01 |
| | Two creek | 129.39 | 7.27 | 59.35 | 7.90 | 6.21 | 17.22 | 1.59 |
| Small burnt | Burnt pine | 7.66 | 0.32 | 66.86 | 1.44 | 21.27 | 10.1 | 0.00 |
| | Fireweed | 5.69 | 0.00 | 53.77 | 2.54 | 30.65 | 13.04 | 0.00 |
| Small unburnt | 1A | 5.10 | 0.93 | 81.02 | 0.00 | 14.36 | 3.69 | 0.00 |
| | Cassidy | 5.87 | 31.74 | 28.14 | 39.41 | 0.00 | 0.15 | 0.03 |
| | Kashka | 3.91 | 41.27 | 22.12 | 27.28 | 0.00 | 5.07 | 4.26 |
| | Millions | 2.43 | 39.29 | 26.64 | 25.40 | 1.32 | 4.25 | 3.10 |
| | Mosquito | 3.07 | 59.16 | 13.92 | 21.62 | 0.00 | 2.64 | 2.67 |
| | Pierre | 2.58 | 35.77 | 48.32 | 7.33 | 4.19 | 0.53 | 3.85 |
| | Sak B | 7.04 | 38.25 | 15.08 | 21.34 | 1.21 | 24.12 | 0.00 |
| | Thistle | 9.01 | 59.03 | 13.81 | 13.44 | 3.71 | 5.29 | 4.71 |
| | Toby | 2.63 | 13.13 | 25.82 | 38.44 | 0.00 | 18.86 | 3.74 |
| | Willow | 15.57 | 42.61 | 27.91 | 23.20 | 1.87 | 3.4 | 1.02 |
| | All area | 739.65 | 13.70 | 56.83 | 9.42 | 6.42 | 12.63 | 0.89 |

* Percentages are computed from AVI using digital mapping techniques.

These statistics are computed by clipping the 1998 AVI (maintained by forestry companies) using each watershed polygon shape file in ArcGIS 8.2. Deciduous species inventoried in the AVI are Aspen poplar, Tamarack, Paper birch and Balsam poplar and conifers inventoried are Jack pine, Lodge pole pine, Sub-alpine fir, Balsam fir, Black spruce, and White spruce.

Mosquito, Thistle and Willow watersheds are dominated by deciduous tree species (see Table 5-10). The satellite detected OG dates (mm/dd) for these watersheds in the year 2001 is given in Table 5-11. EVI based OG dates occur in late May for the deciduous dominated watersheds while NDVI predicts it to be in early to mid-April. NDVI also shows greater variability in the OG date detection for these watersheds.

**Table 5-11:** Onset of Greenup (OG) date for the deciduous dominated watersheds in the year 2001.

| Watersheds | EVIm | EVIz | NDVIm | NDVIz |
|---|---|---|---|---|
| Thistle | 5/25 | 5/22 | 4/1 | 3/30 |
| Mosquito | 5/29 | 5/24 | 4/18 | 4/13 |
| Willow | 5/21 | 5/15 | 4/11 | 4/9 |

The FORWARD study area is close enough to the areas where ground observations are available for the year 2001. A comparison between Table 5-11 and Table 5-9 for deciduous species first, full and leafing dates and satellite OG dates suggests that satellite retrieved OG dates are realistic. Furthermore, based on the reasoning that leaf out date occurs one or two weeks after the full bloom date and that most of the deciduous indicator species (in Table 5-9) have their bloom or leafing date in mid- to late May (mean and median value of full bloom and leaves quarter size event dates are May 19 and May 22, respectively); EVIm (or EVIz since both methods yield similar VPMs) compares best among the four approaches to the observed onset-like events (first, full bloom and leaf size) on the ground for the year 2001. These results add confidence to the satellite retrieved OG dates.

A similar comparison could have been made for the conifer dominated watersheds, Two creek and 1A. However, none of the inventoried (for the AVI) conifer species' bloom dates could be found for the study area and thus are not reported. Although bloom dates of the conifer shrub, Prairie crocus in the year 2001 is reported in the Table 5-9, it is not inventoried in the AVI (though, there is a category of open and closed shrub in the AVI). A meaningful comparison of satellite derived OG dates for the Two creek and 1A watersheds and the conifer shrub 'Prairie crocus' full bloom dates could not be realized.

## 5.3 Characterizing the Spatial and Temporal Dynamics of Vegetation in each Watershed

Any time-series data can be explained in terms of two basic components: seasonality and trend. While the derived VPMs capture the seasonality of the VI time-series data, trend analysis is aided by correlating the mean VPM values and the standard deviation of the VPM. A strong correlation between the two indicates that seasonality fluctuates correspondingly with the overall trend. For example, a correlated peak VI value and peak VI standard deviation would mean that the amplitude of the seasonal changes (variance) increases or decreases with the overall trend. This implies that the relative amplitude of seasonal changes is constant over time and the changes seen in variance are related to the trend. In cases where mean and variance are not correlated, an increase in the variance may indicate areas experiencing stress or a significant change.

For each watershed there is a degree of inherent within watershed variability due to varying conditions of species composition, slopes, soils and other factors (Reed et al. 1994). Therefore, differences in the standard deviation from one year to another may be indicative of stressful conditions over the watershed. Each watershed was checked for consistently increasing or decreasing standard deviation of the time integrated VI value, and rate of greenup, and rate of senescence metrics in the four years to identify any stressful situation. Moreover, mean and variance were also checked for dependency. If a consistent decrease or increase in the mean VPM values was seen during the four years from 2000 to 2003 (e.g. time integrated VI value is decreasing), then this VPM correlated to the standard deviation means that change in the metric values is due to the environmental changes from year to year (which affect the whole watershed in more or less the same manner e.g. high temperature, early greenup and consequently longer length of the growing season, optimum moisture regime etc.). In a case where the mean and standard deviation are not correlated and an increase or decrease is still seen, the situation is considered more serious and may imply a significant landscape change e.g. harvesting, insect attack, drought, flooding, and nutrient depletion in soil, etc. that may affect a portion of the watershed.

The following temporal characterization presents the phenological characteristics and their inter-annual variability for each of the 16 watersheds. The discussion is based on VPMs derived from EVIm approach.

### 5.3.1 Goose watershed

This is a large burnt watershed dominated by conifer tree species (66%) with a moderate 8% of the watershed area as peatlands (see Table 5-10). The OG date occurred in mid-May with the exception of the year 2000 when it occurred in mid-June. The EG date occurred in September with peak vegetation in late July to early August. A consistent advance and delay trend is seen for the EG and peak dates during the four years: earlier peak and earlier end date, or delayed peak and delayed end date. The watershed exhibits a trend of earlier greenup from 2000 to 2003. OG and EG VI value appear to relate to the OG date for the four years in a way that the later the greenup occurred in a year, the higher the OG and EG VI values were observed. The higher rate of greenup is associated with the lower rate of senescence that tends to maintain a consistent length of growing season during the four years. However, length of growing season in 2000 is much shorter (86 days) when compared to the rest of the years (119 to 123 days).

### 5.3.2 Sak A watershed

This burnt watershed is the largest and is mainly coniferous (72%) with a moderate area (9%) of the watershed as peatlands (see Table 5-10). The OG date always occurred in mid- to late May except for the year 2000 when it occurred in early June. The EG and peak date occurred in September and July, respectively for all of the four years. A consistent advance and delay trend is seen in OG and peak date. A higher rate of greenup was associated with a higher rate of senescence that tends to reduce the fluctuation in the length of the growing season over the four years. Length for year 2002 (140 days) is much longer when compared to other years (113 to120 days).

### 5.3.3 Chickadee watershed

This large watershed is dominated almost equally by the deciduous (27%), conifer (32%) and mixed wood (15%) species with a substantial 21% of the watershed area as peatlands (see Table 5-10). The OG, EG and peak date occurred in mid- to late May, early to late September, and mid-July, respectively during the four years. No consistent advance or delay trend is seen in the OG and EG dates. OG VI value is related to the OG date: the earlier the greenup occurred, the lesser the OG VI value that was observed. Rate of greenup for 2001 is significantly higher (1239) when compared to other years (941 for 2000, 860 for 2002 and 697 for 2003).

### 5.3.4 Two creek watershed

This large watershed is mainly coniferous (59%) with substantial 17% of the watershed area as peatlands (see Table 5-10). OG, EG and peak date occurred in early to late May, early to late September and mid-July, respectively, during the four years. A consistent advance and delay trend is seen for the OG and peak date. OG and EG VI value is independent of the OG date; VI value fluctuation for this watershed is insignificant, and it can be assumed that whenever the growing season begins in a year, the corresponding greenness value would remain relatively stable. In other words, the average VI threshold value of greenness can be used to roughly determine the OG for each year. The length of the growing season is longer in 2002 (138 days) when compared to other years (115 to 117 days).

### 5.3.5 Burnt pine watershed

This small burnt watershed is mainly coniferous; 67% of the watershed area is conifer tree species with 21% rangeland and 10% as peatland (see Table 5-10). OG and peak dates occurred in early to late May and early to late July, respectively. An earlier greenup trend is observed from 2000 to 2003. EG date occurred in September and October, resulting in longer length of growing season when compared to other watersheds, especially the four large ones (Goose, Sak A, Two creek, Chickadee) described above. A consistent delay and advance trend is observed for the EG and peak date. OG and EG VI value is positively correlated to OG and EG date, respectively. As the rate of greenup and senescence are positively correlated, this tends to reduce the length fluctuations over the four years. However, length in year 2002 (150 days) is quite longer than in other years (124 in 2000, 135 in 2001, 123 in 2003). Rate of greenup is much high for 2000 (1102) and 2003 (1238) as compared to 2001 (732) and 2002 (745). Overall, the phenology of this watershed is different than the Goose, Sak A, Chickadee, Two creek and Fireweed watersheds in that the length of the growing season is longer, both OG and EG VI values are dependent on the OG and EG dates, and EG dates occur later in October for 2000 and 2002.

### 5.3.6 Fireweed watershed

This small watershed is burnt and is mainly coniferous (54%). 32% of the watershed area is rangeland and 13% is peatland (see Table 5-10). The OG date for the year 2000 occurred in mid-June and for 2001 to 2003 it occurred in mid-May. The peak date consistently occurred at the end of July except for the year 2000 when it occurred in mid-August. The rate of senescence for the year 2000 is high (610) when compared to the other years (585 for 2001, 444 for 2002, and 560 for 2003). This caused the EG date to register in the same month (mid-September) for all of the four years. A consistent delay and advance trend is observed for the OG and peak date, and OG and EG dates are unrelated of their corresponding VI values. The length of the growing season is much shorter in 2000 (96 days) than in other years (116 to 123 days) but this did not impact much on the time integrated VI value because of the higher peak VI value in 2000. The time integrated VI value remained relatively stable over the four years.

### 5.3.7 1A watershed

This small watershed is 81% coniferous and 3.7% of its area is peatland (see Table 5-10). The OG date occurred in early to late May and it's EG was in mid-September except for in 2003 when it occurred in late August. Its peak date occurred in early to late July except in 2001 when it occurred in August. The OG dates are negatively correlated to the EG dates over the four years: the earlier the OG date occurred, the later the end date appeared, indicating the lengthening of the growing season. The length of the growing season is highly variable between the four years: 100 days in 2000, 126 days in 2001, 135 days in 2002, and 91 days in 2003. The OG date and OG VI values were negatively correlated: an earlier greenup is associated with the higher OG VI values. A higher rate of greenup is associated with a higher rate of senescence. Rate of greenup for the year 2001 is very low (363) as compared to other years (for 2000: 1186, for 2002: 805, and for 2003: 1165). Although time integrated VI remains relatively stable over the four years, the variance is decreasing from 2000 to 2003. This indicates that the 1A watershed was experiencing a stressful situation in 2000 and that the ecosystem functioning was improving from then on. It may also imply that the watershed has gone through significant landscape changes from 2000 to 2003. Phenological response of the 1A is quite different from other watersheds because of the lengthening effect of the growing season, negative correlation between OG date and VI value and decreasing time integrated variance from 2000 to 2003.

### 5.3.8 Cassidy watershed

This small watershed is dominated equally by conifer, deciduous and mixed woods species: 32% of the land area is deciduous, 28% coniferous and 39% is mixed woods with almost no peatlands (0.15%) in the watershed (see Table 5-10). The OG date occurred in mid- to late May except in the year 2002, when it occurred in late April. The EG and peak date occurred in early to late September and mid-July, respectively. OG and EG dates are negatively correlated, which tends to lengthen the growing season. In this case, however, the lengthening effect is not seen because of the high positive correlation between the rate of greenup and senescence that reduces length fluctuation. EG and peak date are also negatively correlated. The length of the growing season is highly variable among the four years with longest in 2002: for 2000 it is 119 days, for 2001 it is 99 days, for 2002 it is 165 days, and for 2003 it is 113 days. A significant increase in the variance of time integrated VI value, rate of greenup and rate of senescence from the year 2000 to 2001 may indicate that the watershed was experiencing a stressful situation. This effect may be attributed to the variable vegetation composition in the watershed that responds differently to climatic fluctuations in each of the four years and hence increases the variance over the years. However, this requires further finer-scale investigation.

### 5.3.9 Kashka watershed

This small watershed is mainly deciduous (41%) with almost an equal population of conifer and mixed wood species (22% coniferous and 27% mixed wood). 5% of the watershed area is peatlands and 4.2% is disturbed by industrial and urban activity (see Table 5-10). The OG dates occurred consistently in early to mid-May except in 2003 when it occurred at the end of April. EG dates are highly variable: for 2000 and 2001 the EG occurred in mid-September while for 2002 and 2003 it occurred in mid- to late August. The peak date occurred in early to late July over all of the four years. A consistent advance and delay trend was observed for the OG and EG, OG and peak, and peak and EG dates. Higher OG VI values were associated with lower EG VI values and vice versa. Higher rate of greenup was coupled with a higher rate of senescence and the length of the growing season for year 2002 (98 days) was much shorter than the length in other years (109 to 115 days).

### 5.3.10 Millions watershed

This is the smallest watershed of all and is comprised of 40% deciduous, 27% conifer and 25% mixed wood species with 4.25% peatland and 3.1% industrial and urban activity (see Table 5-10). The OG date occurred in early to mid-May and EG date occurred in mid- to late August except in 2000 when it occurred in early September. The peak date occurred in early July for 2000 and 2003 while it occurred in mid- to late June for 2001 and 2002. This watershed has a consistent OG date but an earlier EG and peak date when compared to other watersheds. The OG and EG VI values are unrelated to the OG and EG dates. No consistence advance or delay trend is seen in the OG and EG dates. The length of the growing season is much shorter in 2001 (75 days) compared to other years (109 to 116 days). The standard deviation of the time integrated VI value and rate of senescence decreases while the rate of greenup metric increases from 2000 to 2002.

### 5.3.11 Mosquito watershed

This small watershed is mainly deciduous (59%) with a small area (2.6%) of peatlands and quite a bit of industrial disturbance (2.6% of the area consists of roads and other related construction) (see Table 5-10). The OG date occurred in mid- to late May except for in 2002 when it occurred in mid-April. The EG date occurred consistently in mid- to late September and the peak date occurred in early to mid-July except for 2002 when it occurred in late June. For earlier peak dates, the EG date tended to occur later. The OG and EG VI values are slightly dependent upon OG and EG dates. The rate of greenup was very high in 2000, 2001 and 2002 (1090, 1619, 1111, respectively) and low in 2003 (807). Overall, this watershed has the highest rates of greenup of all the watersheds. The length of the growing season for year 2002 (164 days) is considerably longer than the other years (128 in 2000, 110 in 2001, and 118 in 2003).

### 5.3.12 Pierre watershed

This small watershed is slightly more coniferous (48%) than deciduous (36%) with almost no peatlands (0.5%). Industrial activity in the watershed is significant: 3.8% of the area is roads and other related construction (see Table 5-10). The OG dates occurred in mid- to late May except for in the year 2000 when the OG occurred in early June. The EG and peak date occurred in mid- to late September and late July, respectively. The peak date for year 2000, however, occurred in early August. A consistent advance and delay trend is seen in the OG and peak dates. For earlier EG dates and lower OG VI values, the EG VI values were higher. The rate of greenup and the EG VI values were consistent over all of the four years (2000 to 2003). The shortest growing season occurred in the year 2000 (102 days) compared to other years (120 days in 2001, 138 days in 2002, and 125 days in 2003).

### 5.3.13 Sak B watershed

This small watershed is 38% deciduous, 21% mixed wood and 15% coniferous with the largest area of peatlands (24%) as compared to other watersheds in the area (see Table 5-10). The OG dates consistently occurred in early to late May, the EG dates occurred in late September to early October and the peak dates occurred in late July to early August. The OG and EG VI values are positively correlated to the OG and EG dates and higher OG VI values are associated with higher EG VI values. The length of the growing season is almost consistent across the four years, and the rate of greenup for 2001 is the highest (1253) compared to other years (730 in 2000, 914 in 2002, and 805 in 2003).

### 5.3.14 Thistle watershed

This small watershed is mainly deciduous (59%) with 5.2% of the watershed area as peatlands and 4.7% as industrial disturbance (see Table 5-10). The OG and peak dates occurred in early to late May and mid-July, respectively. The EG dates for 2000 and 2002 occurred in September while for 2001 and 2003 they occurred in late August. For earlier OG dates, delayed EG dates were observed but a consistent delay and advance trend was observed for the OG and peak dates. The longest growing season occurred in 2002 (133 days) compared to other years (103 days in 2000, 97 days in 2001, and 89 days in 2003). The rate of greenup and senescence is consistent across all of the years (2000 to 2003).

### 5.3.15 Toby watershed

This small watershed is dominated by mixed wood (39%) with 26% conifer and 13% deciduous species. The watershed has a large area of peatlands (19%) (see Table 5-10). The OG dates are highly variable for the four years: the end of May in 2000, early June in 2001, the end of April in 2002, and early May in 2003, possibly due to the mixed composition of the watershed. EG and peak dates most often occurred in early to late September and mid- to late July, respectively, though the peak date for 2000 occurs at the beginning of August. The OG and EG VI values are unrelated to their corresponding dates. The longest growing season occurred in 2002 (148 days) compared to other years (116 days for 2000, 104 days for 2001, and 124 days for 2003). A higher rate of greenup is associated with a lower rate of senescence, and the highest rate of greenup is in the year 2001 (1261) in comparison to other years (857 in 2000, 839 in 2002, and 570 in 2003).

### 5.3.16 Willow watershed

This small watershed is more deciduous (42%) than coniferous (28%) or mixed wood (23%) with 3.4% of the watershed area as peatlands (see Table 5-10). The OG dates occurred in early to late May, the EG dates in early to late September and the peak dates in early to late July. Earlier EG dates are associated with a late peak date and a higher rate of greenup is associated with a lower rate of senescence. The longest growing season is in 2002 (147 days) when compared to other years (123 days in 2000, 125 days in 2001, and 117 days in 2003). The rate of greenup is high and consistent for the years 2000, 2001 and 2002 while for 2003 it is low (743).

While the above inter-annual phenological characterization of each watershed provides mixed results, it describes the vegetation dynamics from year to year in each watershed. A simpler approach to understanding the subtle differences among the watersheds is to eliminate temporal variability from the analysis. In order to do this, the EVIm based VPMs shown in Table 5-2 were first temporally averaged over the four years (2000 to 2003) to come up with a composite response for each of the 16 watersheds. The resulting sample size of 16 observations for each of the 10 VPMs was then correlated to establish relationships among them (i.e. VPMs). In order to check for the most consistent relationship (or any consistent pattern) across the watersheds in these four years, only the significant Pearson correlation coefficients are reported in Table 5-12. Theoretically, the length of the growing season metric should be positively correlated to both of the OG and EG date metrics since length is the difference of the two metrics (OG and EG dates). However, EG date and not the OG date metric was found to correlate positively with the length metric. Moreover, the length of the growing season was also found to positively correlate to the peak date metric. This implies that OG dates were consistent among the 16 watersheds over the four years and both the EG date and peak date metrics exhibits greater variability and sensitivity (when compared to the OG dates) among these watersheds. A positive correlation of 0.54 (see Table 5-12) between the EG date and peak date metrics further suggests that the variation in both of these metrics is consistent.

**Table 5-12**: Pearson correlation coefficients among the VPMs.

| Length vs. EG date | Length vs. OG date | Length vs. peak date | OG vs. peak date | Time int. VI vs. EG date | Rate of senescence vs. EG date | EG date vs. peak date | Onset VI value vs. end VI value | OG date vs. Rt of greenup |
|---|---|---|---|---|---|---|---|---|
| 0.92 | -0.22 | 0.73 | 0.76 | 0.65 | 0.66 | 0.54 | 0.93 | -0.52 |

Likewise, EG and not the OG date metric was found to correlate with the time integrated VI value metric that reinforces the previous finding of a consistent OG date and a variable EG date among the watersheds. A higher rate of senescence was seen for the delayed EG date among the watersheds resulting in a shortening of the length of the growing season. The OG VI value was seen to increase with an increasing EG VI value among the watersheds.

In order to depict a clear picture of how watersheds behave differently from each other in terms of their phenological response, the watersheds were sorted in ascending order based on the temporal average value of each of the 10 VPMs. The results are shown in Table 5-13*a* and 5-13*b*.

**Table 5-13*a***: Watersheds arranged in ascending order based on temporal average VPM values.

| Onset date | | End date | | Peak date | | Onset value | | End value | |
|---|---|---|---|---|---|---|---|---|---|
| Kashka | 5/11 | Millions | 8/22 | Millions | 6/28 | Goose | 2456 | Goose | 2385 |
| Millions | 5/11 | Kashka | 8/29 | Mosquito | 7/6 | Sak B | 2559 | Fireweed | 2521 |
| Cassidy | 5/12 | Thistle | 8/31 | Kashka | 7/12 | Fireweed | 2611 | Mosquito | 2548 |
| Mosquito | 5/13 | 1A | 9/8 | Chickadee | 7/15 | Kashka | 2754 | Kashka | 2605 |
| Sak B | 5/14 | Goose | 9/11 | Cassidy | 7/15 | Mosquito | 2870 | Sak B | 2608 |
| Willow | 5/15 | Chickadee | 9/12 | Thistle | 7/16 | Sak A | 2945 | Willow | 2693 |
| Burnt pine | 5/15 | Cassidy | 9/13 | Willow | 7/17 | Two creek | 2998 | Sak A | 2706 |
| Chickadee | 5/16 | Fireweed | 9/14 | Burnt pine | 7/18 | Thistle | 3033 | Pierre | 2774 |
| Two creek | 5/17 | Two creek | 9/15 | 1A | 7/18 | Pierre | 3035 | Two creek | 2790 |
| Sak A | 5/18 | Sak A | 9/16 | Two creek | 7/20 | Chickadee | 3061 | Chickadee | 2812 |
| Toby | 5/18 | Toby | 9/17 | Sak A | 7/21 | Willow | 3116 | Thistle | 2839 |
| Thistle | 5/19 | Pierre | 9/18 | Toby | 7/22 | Burnt pine | 3138 | Burnt pine | 2879 |
| 1A | 5/19 | Mosquito | 9/19 | Sak B | 7/25 | 1A | 3147 | Toby | 2907 |
| Pierre | 5/20 | Willow | 9/19 | Pierre | 7/26 | Toby | 3205 | 1A | 3007 |
| Fireweed | 5/22 | Burnt pine | 9/24 | Goose | 7/28 | Cassidy | 3419 | Cassidy | 3116 |
| Goose | 5/24 | Sak B | 9/28 | Fireweed | 7/29 | Millions | 3483 | Millions | 3188 |

**Table 5-13*b***: Watersheds arranged in ascending order based on temporal average VPM values.

| Peak value | | Length | | Time-int.VI | | Rt of greenup | | Rt of senescence | |
|---|---|---|---|---|---|---|---|---|---|
| Goose | 4382 | Millions | 103 | Goose | 30668 | Pierre | 672 | Millions | 391 |
| Kashka | 4479 | Thistle | 106 | Kashka | 31758 | Goose | 699 | Kashka | 455 |
| Pierre | 4577 | Goose | 110 | Fireweed | 32090 | Millions | 726 | Goose | 507 |
| Fireweed | 4601 | Kashka | 111 | Millions | 32517 | Fireweed | 762 | Sak A | 510 |
| Millions | 4647 | 1A | 113 | Pierre | 33834 | Kashka | 788 | Burnt pine | 514 |
| Thistle | 4838 | Fireweed | 116 | Thistle | 34912 | Thistle | 806 | Chickadee | 517 |
| Sak A | 4959 | Chickadee | 120 | Sak A | 37591 | Sak A | 810 | Mosquito | 517 |
| Two creek | 5063 | Pierre | 121 | 1A | 37604 | Two creek | 833 | Pierre | 522 |
| 1A | 5071 | Two creek | 121 | Two creek | 38113 | 1A | 880 | 1A | 530 |
| Chickadee | 5120 | Sak A | 122 | Chickadee | 38225 | Toby | 882 | Two creek | 532 |
| Toby | 5209 | Toby | 123 | Toby | 38483 | Sak B | 925 | Thistle | 536 |
| Mosquito | 5215 | Cassidy | 124 | Mosquito | 38702 | Chickadee | 934 | Fireweed | 550 |
| Willow | 5373 | Willow | 128 | Willow | 40856 | Burnt pine | 954 | Willow | 555 |
| Sak B | 5404 | Mosquito | 130 | Sak B | 41108 | Willow | 1012 | Toby | 568 |
| Burnt pine | 5495 | Burnt pine | 133 | Cassidy | 42329 | Cassidy | 1061 | Sak B | 588 |
| Cassidy | 5719 | Sak B | 138 | Burnt pine | 43863 | Mosquito | 1157 | Cassidy | 626 |

Moreover, in order to investigate the linkages between the land use in the FORWARD watersheds and the response of the VPMs, the EVIm based temporally averaged VPMs were correlated to each watershed's percent species composition (Table 5-10) and only the significant correlations are reported in Table 5-14.

**Table 5-14**: Pearson correlation coefficients between the 4 year temporal average of VPMs versus the watersheds' landuse composition.

| OG date vs. % conifer | OG date vs. % deciduous | OG date vs. % mixed woods | EG date vs. % industrial | St_dev of OG vs. % industrial | St_dev of EG vs. % industrial | St_dev of peak vs. % Industrial | St_dev of length vs. % industrial |
|---|---|---|---|---|---|---|---|
| 0.58 | -0.48 | -0.62 | -0.5 | 0.69 | 0.49 | 0.57 | 0.64 |

Key points emerging from the phenological characterization of individual watersheds and the analysis of temporally averaged VPMs are:

- a consistent decrease in variance of the time integrated VI values (variance being uncorrelated to the mean value), from 2000 to 2003 in the 1A watershed may indicate that the watershed is recovering from a stressful situation, possibly a landscape change;

- a significant increase in the variance of time integrated VI values, rate of greenup and rate of senescence from the year 2000 to 2001 in the Cassidy watershed may indicate that the watershed was subjected to a stressful situation during this time period;

- the Thistle and Pierre watersheds have the most consistent rate of greenup and senescence across all of the years (2000 to 2003);

- an early OG date was found to be associated with a higher rate of greenup that, theoretically, should contribute to the lengthening of the growing season. However, a delayed EG date coupled with a higher rate of senescence appeared to offset this effect;

- little variability is seen in the OG dates when compared to the EG and peak dates of the watersheds. This suggests that EG and peak dates are more sensitive indicators of the watershed conditions than the OG dates;

- while the OG date is positively correlated (0.58) to the percent conifer species in the watersheds, it is negatively correlated to the percent deciduous and mixed wood species (-0.48 for deciduous and -0.62 for mixed wood);

- while EG dates for the watersheds are not correlated to any of the percent conifer, deciduous or mixed wood species, they are negatively correlated (-0.5) to the industrial and urban activity in the watersheds. The watersheds with greater industrial and urban disturbance, such as Kashka, Thistle and Millions, are seen to have earlier (and highly variable in four years) EG dates (Table 5-13*a*). Given that length of the growing season is highly correlated (0.92) to the EG date (the later the EG date, the longer the growing season), industrial disturbance seems to shorten the length of the growing season;

- temporal average of the standard deviation of OG, EG, peak date and the length of the growing season are positively correlated to the industrial and urban activities in the watersheds (0.69, 0.49, 0.57 and 0.64, respectively); and finally,

- no significant correlation was found between the percent peatland in the watersheds and any of the VPMs, possibly because the VIs cannot differentiate between different underlying soil types.

## 5.4 Environmental Control of Vegetation Phenology

To assess the environmental control of vegetation phenology, daily meteorological data (temperature and precipitation) from 2000 to 2003, collected at the Whitecourt airport weather station, were correlated to the MODIS EVI and NDVI data. The coefficients are reported in Table 5-15 and Table 5-16. Daily Mean Temperature (MT), Total Rain (TR), Total Snow (TS) and Total Precipitation (TP) values were averaged over the 16-day composite period to align with the MODIS mean EVI and NDVI values that were computed over the whole FORWARD study area. The choice of these meteorological factors is based partly on the availability of the data and partly on the findings of previous research (see Literature Review II section under Phenology: Indicator of Stress and Measure of Ecosystem Resilience), which has indicated that temperature, photoperiod and moisture availability play a major role in the photosynthetic activity of the deciduous and coniferous forested landscape (Reed et al. 1994).

In the year 2000, the Whitecourt airport weather station received 567.6 mm of total precipitation, of which 21.3% occurred as snow; in the year 2001, total precipitation was 471.4 mm, of which 22.2% occurred as snow. These two years (2000 and 2001) can be considered as the "wet" years compared to the year 2002, when total precipitation was 365.3 mm, of which 54.2% occurred as snow and the year 2003, when total precipitation was 407 mm, of which 62.2% occurred as snow.

Table 5-15 and 5-16 suggest that EVI and NDVI are most highly correlated to the mean 16-day temperature, followed by the mean 16-day total rain when compared to the mean 16-day total precipitation for each of the four years, 2000 to 2003. The only exception to this trend is seen for the NDVI in the years 2000 and 2001 when NDVI versus TR correlation is very low, possibly because these two years received a large amount of rainfall when compared to the years 2002 and 2003. The correlation between the VIs (NDVI and EVI) and the mean 16-day total snow values is negative and low (as expected). EVI and the product of MT and TR were found to be more correlated than the simple EVI and MT or EVI and TR. This effect could not be seen for the NDVI, where almost 80% (for the year 2003) of the data variation is explained by the MT alone. EVI and NDVI were also correlated to the product of MT and TP but little to no improvement was noticed in the coefficients.

**Table 5-15**: Pearson correlation coefficients between EVI and meteorological data.

| Year | EVI vs. MT | EVI vs. TR | EVI vs. TS | EVI vs. TP | EVI vs. (MT x TR) | EVI vs. (MT x TP) |
|---|---|---|---|---|---|---|
| 2000 | 0.74 | 0.70 | -0.48 | 0.62 | 0.76 | 0.76 |
| 2001 | 0.70 | 0.61 | -0.45 | 0.55 | 0.62 | 0.63 |
| 2002 | 0.74 | 0.81 | -0.49 | 0.33 | 0.89 | 0.83 |
| 2003 | 0.70 | 0.76 | -0.55 | 0.14 | 0.85 | 0.73 |
| All four years | 0.72 | 0.60 | -0.51 | 0.42 | 0.63 | 0.65 |

**Table 5-16**: Pearson correlation coefficients between NDVI and meteorological data.

| Year | NDVI vs. MT | NDVI vs. TR | NDVI vs. TS | NDVI vs. TP | NDVI vs. (MT x TR) | NDVI vs. (MT x TP) |
|---|---|---|---|---|---|---|
| 2000 | 0.80 | 0.54 | -0.52 | 0.42 | 0.55 | 0.61 |
| 2001 | 0.75 | 0.31 | -0.32 | 0.26 | 0.32 | 0.33 |
| 2002 | 0.79 | 0.78 | -0.57 | 0.25 | 0.74 | 0.79 |
| 2003 | 0.90 | 0.80 | -0.60 | 0.19 | 0.77 | 0.82 |
| All four years | 0.81 | 0.46 | -0.55 | 0.26 | 0.45 | 0.52 |

MT = Mean Temperature, TR = Total Rain, TS = Total Snow, and TP = Total Precipitation.

From the above results, it appears that in the wet years (2000 and 2001) the ecosystem had abundant moisture available and hence the photosynthetic activity was not limited by the TR. However, in the dry years (2002 and 2003) the moisture availability seems to slightly limit or to control the photosynthetic activity in the ecosystem and thus the correlation coefficients are high for both NDVI. This effect is not so pronounced in the EVI correlations, possibly due its lower sensitivity. The single best predictor of vegetation dynamics in the FORWARD study area seems to be the mean temperature. Thus, based on this relationship, time-series plots and regression equations (with scatter plots) were established between the MT and EVI and MT and NDVI over the four years (2000 to 2003) and are presented in Figures 5-4 to 5-9. These plots were also established for each of the years 2000 to 2003, separately, to provide for a clear insight into the yearly variation and are presented in Appendix C in Figures C-1 to C-16.

EVI behaves differently than NDVI when the EVI scatter and time-series plots are closely observed. For all of the years, EVI exhibits a lower correlation with MT than the NDVI (see Table 5-15 and 5-16). Specifically, EVI does not correlate well to the below-zero extremely cold temperatures from January to April: for decreasing temperatures, the EVI values do not fall (decrease) correspondingly (see the dotted circles on the EVI time-series plot). This behavior can be attributed to the abnormally high response of EVI algorithm to the snow covered ground. Moreover, the scatter plot for below 5 °C temperature versus EVI for 2000 to 2003 depicts no correlation between EVI and MT. It is only after snow melt (above 5 °C) that the EVI and MT relationship is established (see Figure 5-8).

NDVI, on the other hand, registers extremely low vegetation values and thus corresponds well to the MT variation. Comparing the NDVI time-series plots among different years, the year 2001 plot exhibits a unique behavior (see the dotted circle on the NDVI time-series plot). Raw NDVI values are much higher in winter when compared to the winter values in other years. This can be attributed either to the faulty raw NDVI values in the data or that the landscape was not completely covered with snow, causing the NDVI to register higher values during the winter. The latter explanation can be supported by the fact that the year 2001 had the highest winter temperatures compared to the other years (2000, 2002 and 2003) that may have caused intermittent snow melt in the study area. This explanation can also be used to explain the 'funneling' effect caused by the inconsistent, high and low NDVI values for the extremely low temperatures (-20 °C to +5 °C) seen in Figure 5-7. The intermittent snow melt in the study area might have caused the NDVI to register very high (for the bare ground) and very low (for the snow) values, resulting in almost no correlation. It is only after snow melt (above 5 °C) that the

NDVI and MT relationship is established (see Figure 5-9). A more flat and weaker $R^2$ NDVI versus above 5 °C MT relationship in Figure 5-9 when compared to the EVI versus above 5 °C MT relationship in Figure 5-8 clearly portrays the saturation aspect of NDVI algorithm in high biomass regions such as FORWARD study area.

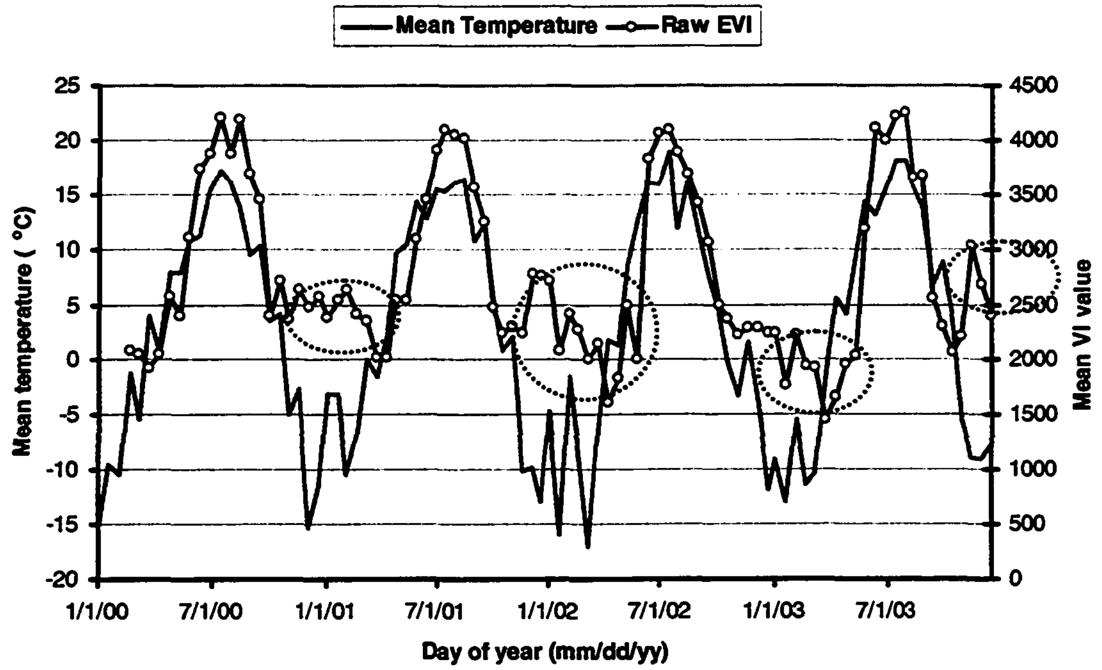


**Figure 5-4**: Time-series plot of mean temperature and EVI over 2000 to 2003.

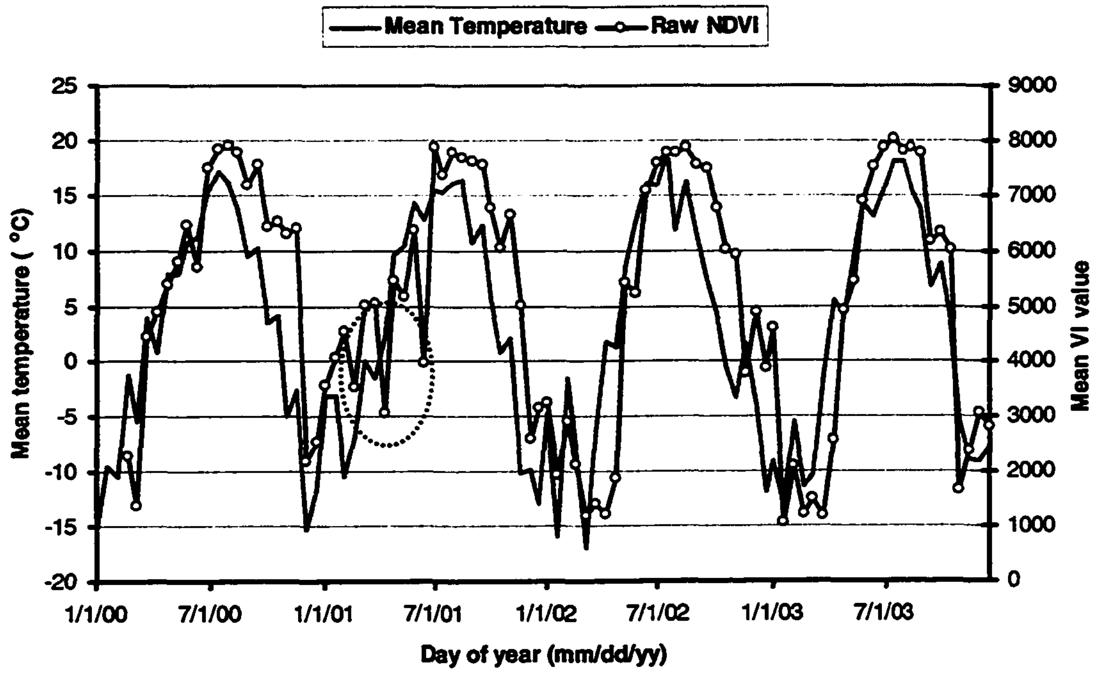


**Figure 5-5**: Time-series plot of mean temperature and NDVI over 2000 to 2003.

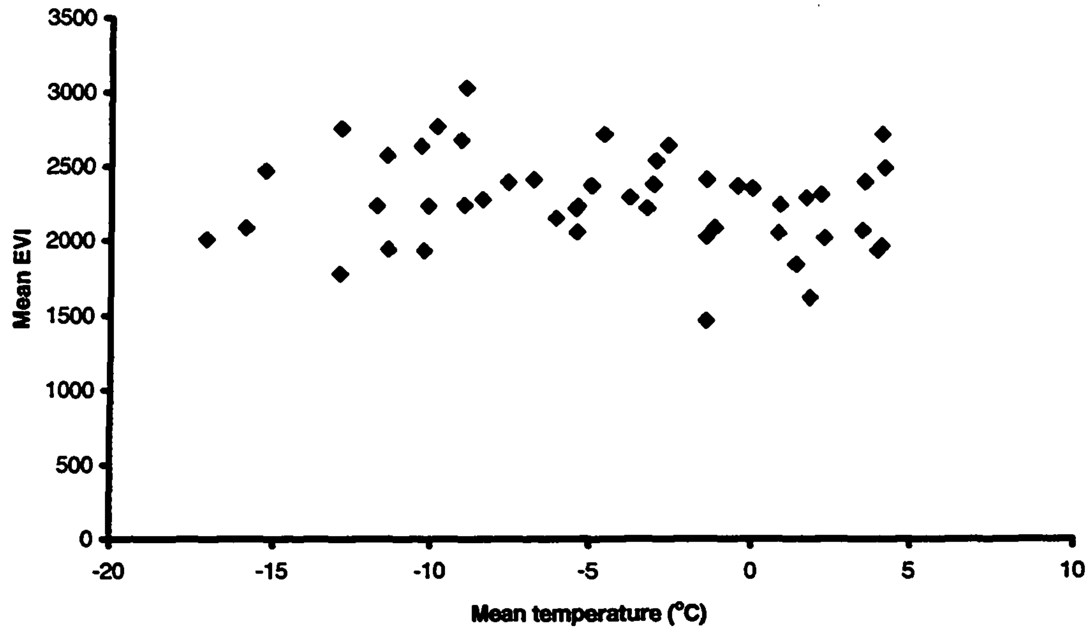


**Figure 5-6**: Scatter plot for below 5 °C temperature versus EVI for 2000 to 2003.

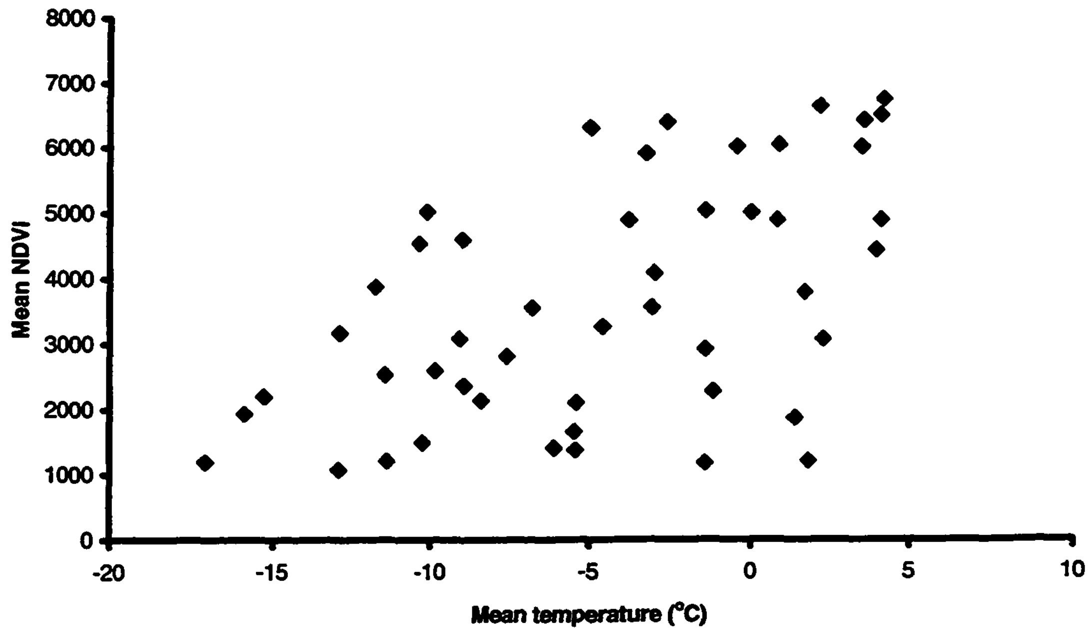


**Figure 5-7**: Scatter plot for below 5 °C temperature versus NDVI for 2000 to 2003.

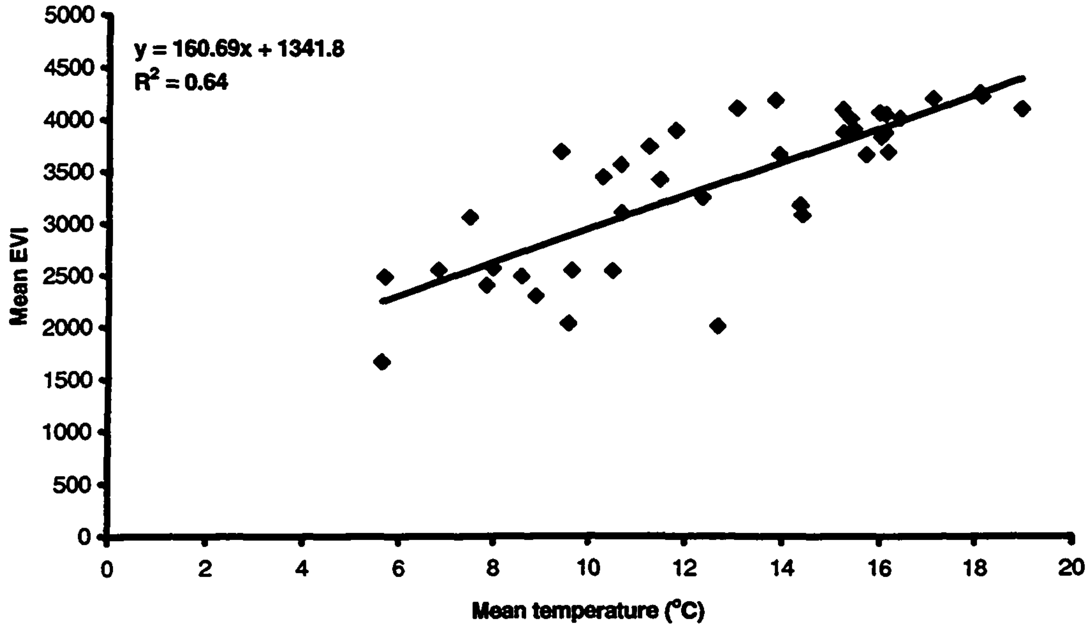


**Figure 5-8**: Scatter plot for above 5 °C temperature versus EVI for 2000 to 2003.

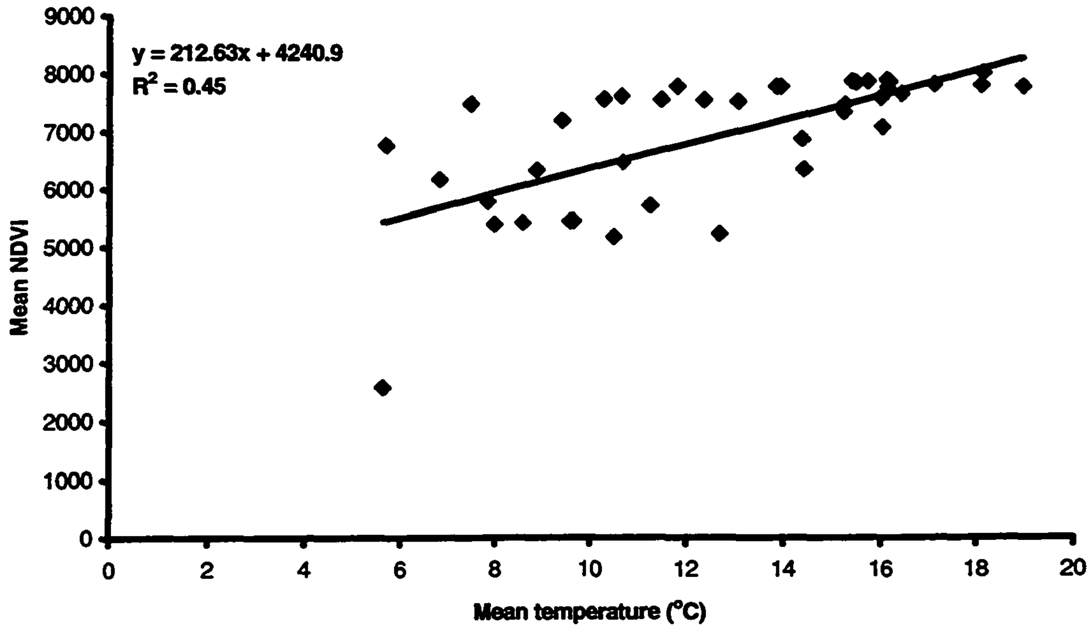


**Figure 5-9**: Scatter plot for above 5 °C temperature versus NDVI for 2000 to 2003.

## 5.5 Biomass Accumulation in the Study Area

The time integral of the NDVI over the growing season has been correlated with Net Primary Production (NPP) (Running and Nemani 1988; Prince 1991; Justice et al. 1985; Tucker and Sellers 1986). NPP approximately equals the actual amount of organic matter created by green plants i.e. the biomass accumulation. NDVIm based time integrated VI values for each of the 16 watersheds have been reported in Table 5-4.

Growing Degree Days (GDD) above 0 °C and 5 °C for 2000 to 2003 recorded at the Whitecourt airport weather station is provided in Table 5-17. The GDD above 0 °C for the years 2000 to 2003 compare well to the longer-term mean GDD value of 2319.1, which is computed using data of at least 15 years from 1971 to 2000 for this weather station (Environment Canada 2003*c*). However, this is not the case for the GDD above 5 °C value: the longer-term mean of 1289.1 (Environment Canada 2003*c*) is much lower than the GDD above 5 °C values for the years 2000 to 2003. This discrepancy can be attributed to error in the meteorological data. Table 5-17 presents time integrated VI values computed over the whole FORWARD area based on EVIm and NDVIm approaches.

**Table 5-17**: Time integrated VI values for NDVIm and EVIm approaches and GDD in 2000 to 2003.

| Year @ approach | Time integrated VI | GDD above 0 °C | GDD above 5 °C |
|---|---|---|---|
| 2000 NDVIm | 88302.33 | 2180.2 | 2063.6 |
| 2000 EVIm | 37613.90 | | |
| 2001 NDVIm | 96149.63 | 2422.1 | 2272.4 |
| 2001 EVIm | 35960.84 | | |
| 2002 NDVIm | 85882.88 | 2165.5 | 2032.6 |
| 2002 EVIm | 38756.25 | | |
| 2003 NDVIm | 89259.14 | 2428 | 2327.1 |
| 2003 EVIm | 35464.39 | | |

NDVIm time integrated VI values in four years (2000 to 2003) are positively correlated to the GDD above 0 °C and above 5 °C (0.73 and 0.64, respectively) that indicates that biomass accumulation is dependent on the availability of heat over the same year. The EVIm time integrated VI values are perfect-negatively correlated (-0.96

and -0.97, respectively) that does not make sense. However, little is known about the EVIm derived time integrated VI value.

The years 2001 and 2003 had the highest GDD (2422 and 2428, respectively) compared to 2000 and 2002 (2180 and 2165, respectively). The highest time integrated NDVI value of 96149 (Table 5-17) is seen for the year 2001, followed by the year 2000, when it was 88302. Both of these years were quite wet because the total rain recorded in 2000 and 2001 was 484.1 mm and 393.9 mm, respectively, compared to 2002 and 2003, when it was 204.8 mm and 208.7 mm, respectively. Moreover, year 2001 also had a higher GDD. A higher time integrated NDVI value can be seen for the dry year 2003 than for the dry year 2002, possibly because of the higher GDD in the year 2003. It seems that time integrated NDVI value (biomass accumulation) is a function of GDD and moisture availability over the same year.

## 5.6 Discussion

Results from the VPMs show a strong coincidence with ground based phenological observations near the study area. These ground based phenological observations (Table 5-9), while limited to only year 2001 and thus certainly not a complete validation dataset, are extremely valuable and reliable since individual observers have reported these blooming events.

When analyzing the results, it is important to consider that the mean and standard deviation of VPMs were derived for only vegetated pixels within each watershed, ignoring all of the zero pixels that represent non-vegetated elements of the landscape (water bodies, roads, burnt forest, and other industrial activities). These zero values were not included in the mean VPM calculation because they would bias the mean towards the lower end. As a result, timings of major events would be seen much earlier than what is shown now, depending on how many zero pixels are present within each watershed. Removing zero pixels from the mean VPM computation essentially means that the effect of non-vegetated pixels on the phenological behavior of each watershed has been removed. This, of course, is desirable when the objective of the study relates only to the vegetation portion of the landscape such as when we must accurately determine the OG and EG dates of the vegetation in order to model the impact of global warming or to compute GDD, for example. However, if the objective of the study is to investigate the response of a function in which the non-vegetated portions of the landscape do play a role e.g. seeking interrelationships between vegetation parameters (such as VPMs) and water quality and quantity variables (nutrient export to the stream, flow generated, etc.), the zero pixels must be included in the mean VPM computation. To assess the effect of non-vegetated elements of the landscape on the phenological behavior of FORWARD watersheds, mean VPMs computed, excluding zero pixels, were subtracted from mean VPMs including zero pixels. The difference tables for EVIm and NDVIm approaches are presented in Appendix C as Table C-5 and C-6, respectively. For ease of interpretation, temporal averages over the four years (2000 to 2003) for these difference tables were also calculated and watersheds were arranged in ascending order for each VPM. The averaged tables are presented in Appendix C as Table C-7 and C-8, and provide an idea of the watersheds that are most affected by removing the zeroes from the mean VPM computation. The zero effect is investigated for only EVIm and NDVIm approaches because the effect was found to be the same for the EVIm, EVIz and NDVIm, NDVIz approaches.

A major source of subjectivity introduced in this research is watershed delineation, which can significantly impact mean VPM values. Some landscape changes (mostly harvest) have also occurred which were not updated in the AVI used in this study. Moreover, the four years data available from the MODIS VI dataset is inadequate for accurately characterizing the inter-annual variability of vegetation dynamics in the study area. The low temporal resolution (16-days) of the time-series VI data further limited the utility of this analysis. The lack of watershed level meteorological data also limited inter-comparison efforts, and the inter-annual variability of VPMs over the study area could not be explicitly stated. Results must be analyzed carefully since patterns of associations have been reported which, instead of deductively advocating causation, point towards factors that probably play an important role in the function of interest and hence need further investigation at a finer scale.

# Chapter 6

## Conclusions and Recommendations

MODIS VI temporal profiles were used to compare inter-annual vegetation seasonal and phenologic activity, peak greenness, length of growing season, onset of greenness and senescence, biomass accumulation and derivative rates of greenup and senescence on a watershed level in the Boreal forest landscape. This research attempts to characterize vegetation dynamics in terms of VPMs that have the potential to evaluate variability or stability (Reed et al. 1994) of watershed phenology, to provide an early warning of ecosystem stress, to support management decisions related to maintaining forest productivity and to serve as sustainability criteria that the forestry industry can use to report to regulatory agencies.

The following conclusions are drawn from the analysis:

- statistically insignificant differences are found between the Zhang and Zhang modified approach based VPMs for the MODIS 4 year data (2000 to 2003);
- statistically significant differences are found between the EVI and NDVI based VPMs for the MODIS 4 year data (2000 to 2003);
- onset of greenup dates for the Zhang approach qualitatively appear earlier than the onset dates for the Zhang modified approach when both are compared to ground based observations;
- EVIm based VPMs coincide well with ground based budburst observations near the study area when compared to the NDVIm based VPMs;

- while EVIm based onset of greenup corresponds to the canopy greenup, the NDVI based onset of greenup corresponds to the snowmelt event and under-storey greenup;

- MODIS NDVI and EVI data acquired over the FORWARD study area is found to have a weak per-pixel correlation and the effect of data treatment on the correlation coefficient is mixed. This weak correlation is contrary to the statements in the relevant literature;

- a consistent decrease in variance of the time integrated VI values from 2000 to 2003 in the 1A watershed may indicate that the watershed is recovering from a stressful situation, possibly a landscape change;

- a higher percentage of conifer species tends to delay the onset of the growing season in the watershed, while a higher percentage of deciduous and mixed wood species favors earlier onset. Overall, the correlation among the VPMs and between the VPMs and watershed land use percentages are found to be consistent with the relevant literature;

- variability in the OG dates across FORWARD 16 watersheds is much less than the variability in the EG and peak dates. This suggests that the EG and peak dates are more sensitive indicators of watershed conditions than the OG dates and may serve as the sustainability indicators of a watersheds' health;

- increasing industrial activities (such as road construction and other related disturbances) in a watershed appear to shorten the length of the growing season by favoring an early end of the greenup date. Moreover, an increase in the variance of the EVIm derived OG, EG, peak date and the length of the growing season metrics is seen for increasing industrial activities;

- biomass accumulation appears to be a function of GDD and the moisture availability over the same year;

- the NDVI based time integrated VI value metric performed consistently with the statements of previous researchers.

- while the NDVIm time integrated VI value represents biomass accumulation, the EVIm time integrated VI value metric remained elusive, and difference in response of the two metrics could not be well characterized;

- the MODIS 16-day mean EVI and NDVI values, computed by spatially averaging over all the FORWARD study area, were found to positively correlate to the 16-day mean temperature recorded at Environment Canada's Whitecourt airport weather station i.e. the mean temperature is a very good predictor of the EVI and vice versa.

- correlation coefficients between NDVI and the total rain recorded at the Whitecourt weather station indicates that in wet years (2000 and 2001), the vegetation activity was independent of the total rain: the ecosystem was not limited by the moisture availability since plenty of moisture was available. This effect is less pronounced for the EVI versus total rain coefficients, possibly due to lower sensitivity of the EVI; and finally,

- the EVI did not correlate well to extreme below-zero temperatures when compared to the NDVI.

The results, while positive in some respects, indicate no general trend from 2000 to 2003 over the FORWARD study area. Moreover, the analysis of spatial variability of these trends did not reveal any substantial watershed differences.

The results above elaborate the different responses of the two VIs (EVI and NDVI) in characterizing vegetation dynamics. EVI is reported to be more useful for upper canopy investigation in primarily forested landscapes; NDVI, on the other hand, has well-established and well-characterized responses for studying biomass accumulation. However, both the indices have marked shortcomings in characterizing the vegetation covered with snow. NDVI exhibits extremely low and EVI exhibits extremely high vegetation values for the snow presence on the ground. The answer to the question of whether EVI or NDVI is best suited to characterize landscape phenology depends on the goals of the researcher. Factors such as canopy closure, land use land cover type, and presence of snow, etc. must be considered before deciding which VI to use. The results must then be interpreted within the context of defined study objectives, acknowledging the differences between the two VIs.

These results have considerable implications for natural resource monitoring. As management perspectives are shifting away from riparian vegetation analysis to larger landscape investigations, many countries, including Canada, are developing national-scale monitoring protocols for the monitoring of natural resources (EMAN 2003) that require broad scale screening indicators as surrogates of ecological health (Griffith et al. 2002). The Ontario Ministry of Natural Resources, Forest Research Institute (1997) reported that "measurable indicators of forest condition are urgently needed in Ontario and elsewhere." The Ministry had previously initiated the Bioindicators of Forest Sustainability project, which attempted to develop a Forest Condition Rating (FCR) system that uses RS spectral features to identify forests on a quantitative scale from "healthy" to "stressed". This research, hence, is another effort to explore the potential of RS VPMs to serve as screening indicators for use in such monitoring programs as Environment Canada's Ecological Monitoring and Assessment Network (EMAN).

Identification of peak photosynthetic levels in the growing season has considerable implications for evapotranspiration studies (Senay and Elliott 2000) whereby temporal variability in water use patterns throughout the growing season can be marked. The VPMs provide a temporal distribution of the vegetation cycle and hence, the nitrogen, phosphorus, and nutrient uptake cycles can be adjusted using the VPM information for each year. For example, water use and nutrient uptake is expected to be a maximum at the peak photosynthetic activity and lowest at the end of the growing season. Moreover, the precipitation intercepted and the subsequent runoff generated before and after the peak photosynthetic activity in a watershed can be expected to carry different levels of nutrient loading. The implications of phenological information for hydrological modeling, however, have not been completely explored yet. Even the most comprehensive hydrology models, such as the Soil Water Assessment Tool (SWAT) by the USDA, assume an average or optimum uptake of nutrients by the vegetation throughout the growing season (or in a year). The scarce incorporation of vegetation phenology information in ecosystem and hydrological simulation models to date, may be attributed not so much to the absence of interest as to the problems associated with acquiring this kind of information (White et al. 1997). Imaging frequency and synoptic coverage of advanced satellite sensors have finally made it possible to extract the phenological timing and growth phases of earth's vegetation.

The results also have implications for water quality studies. Johnson et al. (1997) summarized many studies that relate water quality with land use land cover (LULC). Particularly, nitrogen and phosphorus have been found to have strong relationships with LULC (Lowrance et al. 1985; Bolstad and Swank 1997). However, LULC is a temporally static characterization and does not account for seasonal, inter-annual or directional changes (Hobbs 1990) as VPMs do. Griffith (2002) found that VPMs were more highly correlated to water quality parameters than simple LULC proportions. VPMs can also be correlated with insect emergence time for pest control purposes and can be used to indicate the optimal times to apply herbicides and insecticides.

This research is unique because it attempts to investigate satellite derived phenology (VPMs) on a watershed scale and a small area (740 $km^2$) and with a 250 m resolution pixel. Scale differences may have an impact (1 km versus 500 m versus 250 m spatial resolution) on the findings but investigating scale dependencies of VPMs was beyond the scope of this study. Previous research has focused on a large area (global focus) for the VPM extraction on the 'land cover level' with a spatial resolution of 1 km or more, and reported that the results are consistent with the expected phenological response of various land cover types. VPM information, however, is not well suited for land use land cover (LULC) classification, and different land cover types may have the same phenological response depending on various factors. Since VIs are correlated to photosynthetic activity (for the Boreal biome where moisture is not a limiting factor), VPMs provide information about the physiological rather than the structural condition of the watersheds. This photosynthetic activity for deciduous canopies is highest in newly expanded, high chlorophyll leaves, and much reduced in older, low chlorophyll leaves that are approaching dormancy (Reich et al. 1995). Moreover, for all species, photosynthetic activity is sensitive to age, soil type, drought and flooding, genetic variation within the same species, and many other factors (see Literature Review II under Phenology: Indicator of Stress and Measure of Ecosystem Resilience). Therefore, different percentages of canopy cover (White et al. 1997) and LULC proportions (e.g. a deciduous stand and a conifer stand) may be associated with the same photosynthetic potential.

Many researchers, including Reed et al. (1994), typically employed Loveland et al. (1993) classification with 159 land cover types. White et al. (1999), in contrast, included only six land cover types based on Nemani and Running (1995) purely RS classification, in their phenology model development, and argued that the inclusion of detailed land cover classes might render more accuracy but would require a large amount of ancillary information that is difficult or impossible to acquire for 'large areas', making regular updates at global scale impractical. This research is based on the idea that the phenological characterization of a small area can be monitored over a few years, and that the detailed ancillary (land cover, species and meteorological) information, with regular updates, can be acquired to accurately understand spatial and inter-annual variation and the factors responsible for this variation. The main caveat in this research is the small sample size of the data (four years) to calculate the correlation coefficients that were used to characterize inter-annual variability of the phenological responses. Use of longer term time-series VI data (as it becomes available) with more sophisticated quality control, such as the one recommended by Didan and Yin (2002), and the inclusion of detailed, species level land cover information beyond the conifer, deciduous and mixed woods resolution, might allow for more accurate inter-watershed differences characterization. Moreover, RS snow cover data must be employed in conjunction with the EVI and NDVI data to capture the vegetation dynamics in the snow covered areas.

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# Appendix A: MODIS Data Validation

**Table A-1:** Summary of data sets used in MODIS VI validation efforts (Huete et al. 1999).

| Campaign/Data Set | Dates | Sensors | Purpose |
|---|---|---|---|
| Chile - GLCTS (Test Sites) | September, 1996 | Cimel, Exotech, (Ground and Light Aircraft) | •VI-saturation test (rainforest)<br>•VI-baseline test (hyper-arid)<br>•VI-threshold test (arid/semiarid)<br>•*VI-biophysical (all)* |
| LTER Sites, U.S.A. (Long-Term Ecological Research) | Ongoing, 1992 - (Annual and Seasonal) | TM, AVHRR, ASAS, MAS | •VI-seasonality, compositing<br>•Field correlative measures<br>- biophysical<br>- phenologic |
| SCAR-B (Brasil) | August to September, 1995 | MAS, AVIRIS, Exotech, Cimel | •VI-smoke analysis<br>•VI-saturation (bandwidths)<br>•VI-biophysical<br>•Continuity analysis (AVHRR, MODIS) (Tropical forest/cerrado) |
| HAPEX-Sahel (Niger, Africa) | August to October, 1992 | ASAS, TM, Exotech, Cimel | •VI-biophysical, angular compositing threshold (Semiarid) |
| OTTER Transect (Oregon) | 1992 | ASAS, TM | •VI-biophysical, angular, compositing saturation (Forests) |
| Monsoon '90 | August to September, 1990<br>September, 1991<br>Seasonal, 1992 | ASAS, AVIRIS, TM, Exotech, (Air, Ground), Spectron | •VI-angular, compositing threshold<br>•VI-seasonality, biophysical (semiarid) |
| FIFE (Kansas, USA) | May to September, 1987 and July to August, 1989 | ASAS, TM | •VI-biophysical, angular, compositing (grassland) |
| BOREAS (Canada) | August to September, 1995 | ASAS, TM | •VI-biophysical, angular, smoke, compositing (boreal forest) |
| Global-TM/AVHRR GLCTS Pathfinder | 1985 to Present | TM, AVHRR | •VI intercomparisons (global)<br>•VI-compositing |
| MAC (Maricopa Agricultural Center, Arizona) | 1986 to Present | TM, Exotech, Sun Photometer, BRDF | •VI-seasonal; biophysical, angular<br>•Dry-wet backgrounds |

**Command used for File-level (metadata) quality check**

Command prompt:\ Dowloaded Raw data>read_meta –meta= AUTOMATICQUALITYFLAG, QAPERCENTMISSINGDATA, QAPERCENTOUTOFBOUNDSDATA, QAPERCENTCLOUDCOVER, QAPERCENTINTERPOLATEDDATA , QAPERCENTGOODQUALITY, QAPERCENTOTHERQUALITY, QAPERCENTNOTPRODUCEDCLOUD, QAPERCENTNOTPRODUCEDOTHER, EVI250M16DAYQCLASSPERCENTAGE, QAPERCENTPOORQ250MOR500M16DAYEVI, PGEVERSION, SCIENCEQUALITYFLAG, SEAPROCESSED

**Command used for Pixel-level (SDS) quality check**

Command prompt:\Dowloaded Raw data>unpack_sds_bits -of=unpack_1 -sds="250m 16 days NDVI Quality","250m 16 days EVI Quality" -bit=0-1,2-5,6-7,11-12 MOD13Q1.A2000049.h11v03.004.2002359025816.hdf

# Appendix B: Overview of MODIS QA Approach

**Table B-1:** Descriptions of the VI QA SDS (MLST 2004).

| Bit No. | Parameter Name | Bit Comb. | Description |
|---|---|---|---|
| 0-1 | VI Quality (MODLAND Mandatory QA Bits) | 00 | VI produced with good quality |
| | | 01 | VI produced but with unreliable quality and thus examination of other QA bits recommended |
| | | 10 | VI produced but contaminated with clouds |
| | | 11 | VI not produced due to bad quality |
| 2-5 | VI Usefulness Index | 0000 | Perfect quality (equal to VI quality = 00: VI produced good quality) |
| | | 0001 | High quality |
| | | 0010 | Good quality |
| | | 0011 | Acceptable quality |
| | | 0100 | Fair quality |
| | | 0101 | Intermediate quality |
| | | 0110 | Below intermediate quality |
| | | 0111 | Average quality |
| | | 1000 | Below average quality |
| | | 1001 | Questionable quality |
| | | 1010 | Above marginal quality |
| | | 1011 | Marginal quality |
| | | 1100 | Low quality |
| | | 1101 | No atmospheric correction performed |
| | | 1110 | Quality too low to be useful |
| | | 1111 | Not useful for other reasons |
| 6-7 | Aerosol Quantity | 00 | Climatology used for atmospheric correction |
| | | 01 | Low |
| | | 10 | Intermediate |
| | | 11 | High |
| 8 | Atmosphere Adjacency | 0 | (No) No adjacency correction performed |
| | | 1 | (Yes) Adjacency correction performed |
| 9 | Atmosphere BRDF Correction | 0 | (No) No atmosphere-surface BRDF coupled correction performed |
| | | 1 | (Yes) Atmosphere-surface BRDF coupled correction performed |
| 10 | Mixed Clouds | 0 | (No) No mixed clouds |
| | | 1 | (Yes) Possible existence of mixed clouds |
| 11-12 | Land/Water Mask | 00 | Ocean/inland water, Shallow ocean, Moderate and continental ocean, Deep ocean, Deep inland water |
| | | 01 | Coastal region, Ocean coastlines, lake shorelines, Shallow inland water |

| | | | |
|---|---|---|---|
| | | 10 | Wetland Ephemeral water |
| | | 11 | Land |
| 13 | Snow/Ice | 0 | (No) No snow/ice |
| | | 1 | (Yes) Possible existence of snow/ice |
| 14 | Shadow | 0 | (No) No shadow |
| | | 1 | (Yes) Possible existence of shadow |
| 15 | Compositing Method | 0 | BRDF composite method used for compositing |
| | | 1 | Constraint view angle MVC (CV-MVC) method used for compositing |

**Table B-2:** Relationship between the MODLAND mandatory per-pixel QA bits and QA metadata objects (MLST 2004).

| VI Quality Bit Combination | Corresponding QA Metadata Object |
|---|---|
| 00: VI produced, good quality | QAPercentGoodQuality |
| 01: VI produced, unreliable quality | QAPercentOtherQuality |
| 10: VI produced, contaminated with cloud | QAPercentNotProducedCloud |
| 11: VI not produced due to bad quality other than cloud | QAPercentNotProducedOther |

**Table B-3:** VI Usefulness Index scaling method for the MOD13Q1 product (MLST 2004).

| Parameter Name | Condition | Score |
|---|---|---|
| Aerosol Quantity | If aerosol climatology was used for atmospheric correction (00) | 2 |
| | If aerosol quantity was high (11) | 3 |
| Atmosphere Adjacency Correction | If no adjacency correction was performed (0) | 1 |
| Atmosphere BRDF Correction | If no atmosphere-surface BRDF coupled correction was performed (0) | 2 |
| Mixed Clouds | If there possibly existed mixed clouds (1) | 3 |
| Shadow | If there possibly existed shadow (1) | 2 |
| View zenith angle ($q_v$) | If $q_v > 40°$ | 1 |
| Sun zenith angle ($q_s$) | If $q_s > 60°$ | 1 |

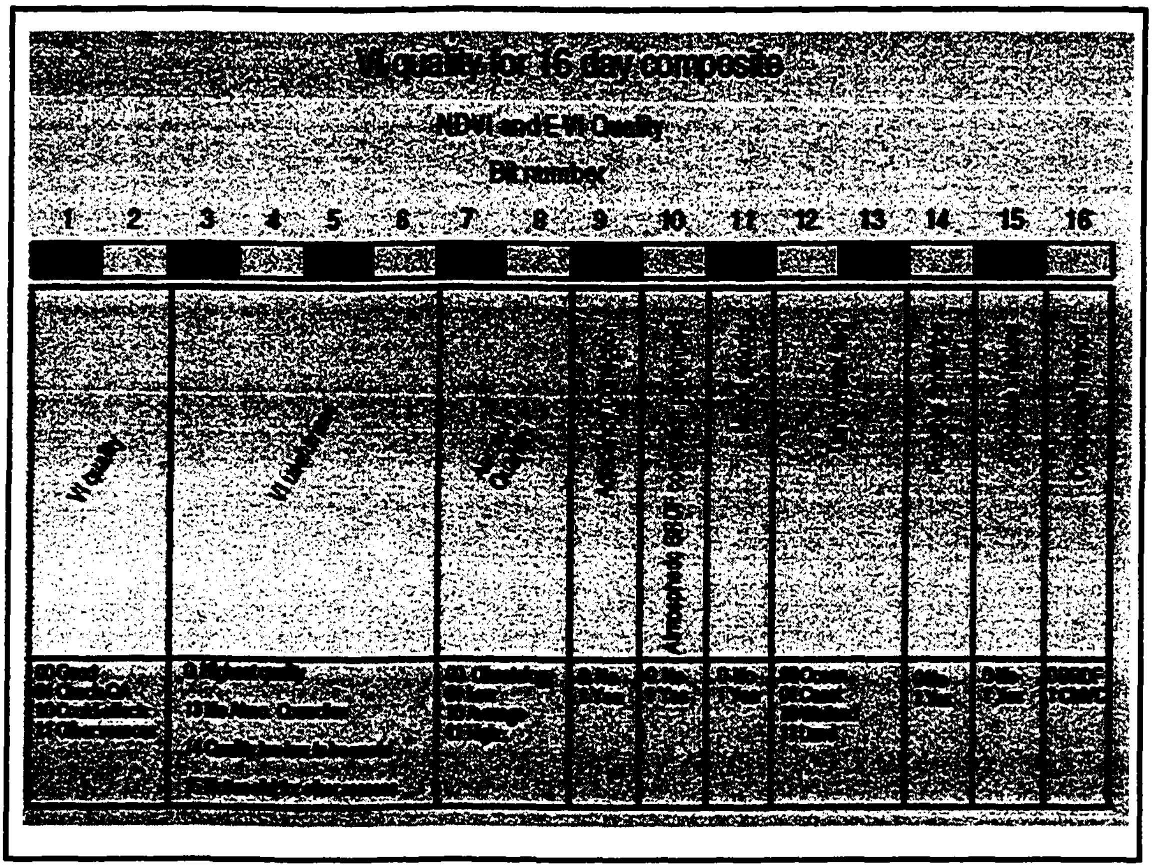


**Figure B-1:** MODIS VI QA SDS bit map. Source: MODIS Land Science Team (MLST) (2004).

**Table B-4:** List of the QA metadata objects for the MOD13Q1 product (MLST 2004).

| Object Name | Object Type | Group Name | Description | Level |
|---|---|---|---|---|
| AutomaticQuality Flag | ECS Mandatory QAFlags, Text | InventoryMetadata in *CoreMetadata.0* | Result of an automatic quality assessment performed during product generation<br>Valid value: "Passed", "Suspect", or "Failed" | Per-SDS, Per-Tile |
| AutomaticQuality FlagExplanation | ECS Mandatory QAFlags, Text | InventoryMetadata in *CoreMetadata.0* | Explanation of the result of the automatic quality assessment<br>Valid value: Up to 255 characters<br>Sample value: "Run was successful But no land data found/processed" | Per-SDS, Per-Tile |
| OperationalQuality Flag | ECS Mandatory QAFlags, Text | InventoryMetadata in *CoreMetadata.0* | Result of an manual, non-science quality assessment performed by production facility personnel after production<br>Valid value: "Passed", "Suspect", "Failed", "Inferred Passed", "Inferred Failed", "Being Investigated", or "Not Being Investigated" | Per-SDS, Per-Tile |

| | | | | |
|---|---|---|---|---|
| OperationalQuality FlagExplanation | ECS Mandatory QAFlags, Text | InventoryMetadata in *CoreMetadata.0* | Explanation of the result of the manual, non-science quality assessment<br>Valid value: Up to 255 characters<br>Sample value: | Per-SDS, Per-Tile |
| ScienceQuality Flag | ECS Mandatory QAFlags, Text | InventoryMetadata in *CoreMetadata.0* | Result of an manual, science quality assessment performed by science computing facility personnel after production<br>Valid value: "Passed", "Suspect", "Failed", "Inferred Passed", "Inferred Failed", "Being Investigated", or "Not Being Investigated" | Per-SDS, Per-Tile |
| ScienceQuality FlagExplanation | ECS Mandatory QAFlags, Text | InventoryMetadata in *CoreMetadata.0* | Explanation of the result of the manual, science quality assessment<br>Valid value: Up to 255 characters<br>Sample value: | Per-SDS, Per-Tile |
| QAPercent InterpolatedData | ECS Mandatory QAStats, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of interpolated data in the tile<br>Valid value: 0~100<br>Sample value: 12 | Per-SDS, Per-Tile |
| QAPercent MissingData | ECS Mandatory QAStats, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of missing data in the tile<br>Valid value: 0~100<br>Sample value: 8 | Per-SDS, Per-Tile |
| QAPercent OutOfBoundData | ECS Mandatory QAStats, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of data in the tile of which values are out of a valid range<br>Valid value: 0~100<br>Sample value: 2 | Per-SDS, Per-Tile |
| QAPercent CloudCover | ECS Mandatory QAStats, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of cloud covered data in the tile<br>Valid value: 0~100<br>Sample value: 15 | Per-SDS, Per-Tile |
| QAPercent GoodQuality | MODLAND Mandatory, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of data produced with good quality in the tile<br>Valid value: 0~100<br>Sample value: "4" | Per-Tile |
| QAPercent OtherQuality | MODLAND Mandatory, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of data produced with unreliable quality in the tile<br>Valid value: 0~100<br>Sample value: "56" | Per-Tile |
| QAPercent NotProducedCloud | MODLAND Mandatory, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of data produced but contaminated with clouds in the tile<br>Valid value: 0~100<br>Sample value: "32" | Per-Tile |
| QAPercent NotProducedOther | MODLAND Mandatory, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of data not produced due to bad quality in the tile<br>Valid value: 0~100<br>Sample value: "8" | Per-Tile |

| | | | | |
|---|---|---|---|---|
| NDVI500M16DAY QCLASS PERCENTAGE | VI Product Specific, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of NDVI data produced with good quality in the tile<br>Valid value: 0~100<br>Sample value: "4" | Per-Tile |
| EVI500M16DAY QCLASS PERCENTAGE | VI Product Specific, Numeric | InventoryMetadata in *CoreMetadata.0* | Percentage of EVI data produced with good quality in the tile<br>Valid value: 0~100<br>Sample value: "4" | Per-Tile |
| QAPERCENT POORQ 500M16DAYNDVI | VI Product Specific, Numeric | ArchivedMetadata in *ArchiveMetadata.0* | Summary statistics (% frequency distribution) of the NDVI usefulness index over the tile<br>Valid format: (N, N, N, N, N, N, N, N, N, N, N, N, N, N, N, N), where N = 0~100<br>Sample value: (4,0,0,0,44,6,18,15,5,0,0,0,0,0,0,8) | Per-Tile |
| QAPERCENT POORQ 500M16DAYEVI | VI Product Specific, Numeric | ArchivedMetadata in *ArchiveMetadata.0* | Summary statistics (% frequency distribution) of the NDVI usefulness index over the tile<br>Valid format: (N, N, N, N, N, N, N, N, N, N, N, N, N, N, N, N), where N = 0~100<br>Sample value: (4,0,0,0,44,6,18,15,5,0,0,0,0,0,0,8) | Per-Tile |

# Appendix C: Analysis of VPMs

**Table C-1**: Standard deviation of EVIz based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date | End date | Peak date | Onset value | End value | Peak value | Length | Time-int.VI | Rt of greenup | Rt of senescence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 37 | 46 | 36 | 756 | 949 | 1367 | 46 | 11811 | 756 | 547 |
| | 2001 | 47 | 35 | 26 | 669 | 512 | 673 | 46 | 10086 | 333 | 200 |
| | 2002 | 35 | 40 | 35 | 909 | 567 | 884 | 41 | 9626 | 447 | 159 |
| | 2003 | 31 | 31 | 31 | 699 | 623 | 737 | 27 | 6372 | 614 | 410 |
| Burnt pine | 2000 | 28 | 24 | 27 | 771 | 500 | 905 | 32 | 9065 | 643 | 411 |
| | 2001 | 27 | 19 | 25 | 690 | 509 | 512 | 32 | 7793 | 446 | 146 |
| | 2002 | 42 | 48 | 36 | 792 | 1035 | 694 | 55 | 12240 | 679 | 187 |
| | 2003 | 40 | 21 | 16 | 644 | 772 | 607 | 41 | 8791 | 651 | 120 |
| Cassidy | 2000 | 30 | 44 | 25 | 731 | 1018 | 933 | 40 | 10318 | 525 | 224 |
| | 2001 | 27 | 35 | 26 | 875 | 665 | 1247 | 47 | 11151 | 742 | 481 |
| | 2002 | 42 | 34 | 41 | 794 | 679 | 1048 | 52 | 12274 | 840 | 197 |
| | 2003 | 39 | 14 | 30 | 831 | 577 | 1006 | 38 | 10223 | 497 | 280 |
| Chickadee | 2000 | 41 | 42 | 28 | 735 | 802 | 1047 | 44 | 10568 | 572 | 385 |
| | 2001 | 31 | 41 | 24 | 797 | 710 | 928 | 44 | 10482 | 590 | 239 |
| | 2002 | 44 | 47 | 39 | 1147 | 712 | 1004 | 48 | 11076 | 675 | 278 |
| | 2003 | 41 | 30 | 33 | 846 | 706 | 776 | 38 | 8418 | 487 | 362 |
| Fireweed | 2000 | 38 | 37 | 24 | 725 | 704 | 724 | 39 | 7202 | 378 | 401 |
| | 2001 | 39 | 46 | 31 | 1350 | 656 | 981 | 44 | 7790 | 670 | 396 |
| | 2002 | 31 | 39 | 34 | 1733 | 687 | 805 | 40 | 8625 | 445 | 182 |
| | 2003 | 27 | 40 | 29 | 594 | 772 | 830 | 37 | 6496 | 382 | 375 |
| Goose | 2000 | 48 | 46 | 23 | 911 | 908 | 721 | 34 | 7393 | 457 | 307 |
| | 2001 | 56 | 40 | 24 | 1030 | 771 | 766 | 53 | 8011 | 410 | 276 |
| | 2002 | 38 | 49 | 35 | 1385 | 892 | 931 | 35 | 8010 | 584 | 270 |
| | 2003 | 32 | 47 | 26 | 965 | 1134 | 701 | 45 | 6080 | 382 | 396 |
| Kashka | 2000 | 43 | 44 | 24 | 764 | 596 | 580 | 56 | 10114 | 259 | 243 |
| | 2001 | 39 | 60 | 25 | 701 | 585 | 924 | 51 | 9730 | 480 | 299 |
| | 2002 | 48 | 70 | 35 | 1016 | 939 | 910 | 40 | 7632 | 422 | 267 |
| | 2003 | 42 | 41 | 35 | 1039 | 712 | 1022 | 41 | 8318 | 672 | 253 |
| Millions | 2000 | 32 | 50 | 30 | 614 | 677 | 602 | 55 | 11963 | 525 | 379 |
| | 2001 | 30 | 39 | 11 | 584 | 483 | 403 | 46 | 9423 | 463 | 249 |
| | 2002 | 57 | 54 | 49 | 804 | 531 | 1449 | 60 | 12679 | 971 | 163 |
| | 2003 | 56 | 36 | 39 | 587 | 432 | 992 | 52 | 10267 | 748 | 204 |
| Mosquito | 2000 | 35 | 40 | 21 | 705 | 832 | 594 | 40 | 9524 | 445 | 218 |
| | 2001 | 19 | 33 | 14 | 884 | 487 | 525 | 33 | 8967 | 501 | 258 |
| | 2002 | 49 | 54 | 37 | 1081 | 932 | 754 | 55 | 11505 | 717 | 169 |
| | 2003 | 38 | 29 | 23 | 936 | 659 | 830 | 35 | 7505 | 400 | 367 |
| Pierre | 2000 | 45 | 55 | 31 | 655 | 912 | 937 | 50 | 11180 | 448 | 477 |
| | 2001 | 56 | 37 | 34 | 798 | 552 | 860 | 66 | 13024 | 453 | 286 |
| | 2002 | 42 | 47 | 42 | 1616 | 659 | 723 | 45 | 10663 | 544 | 253 |
| | 2003 | 35 | 42 | 38 | 543 | 747 | 1081 | 42 | 8670 | 610 | 1077 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sak A | 2000 | 39 | 38 | 30 | 800 | 736 | 997 | 43 | 10947 | 581 | 402 |
| | 2001 | 37 | 34 | 26 | 838 | 607 | 917 | 40 | 8479 | 485 | 266 |
| | 2002 | 41 | 47 | 40 | 1120 | 724 | 985 | 48 | 11309 | 623 | 222 |
| | 2003 | 35 | 33 | 28 | 812 | 728 | 774 | 38 | 8155 | 559 | 313 |
| Sak B | 2000 | 22 | 31 | 24 | 891 | 747 | 788 | 35 | 8639 | 293 | 263 |
| | 2001 | 26 | 32 | 24 | 608 | 799 | 716 | 36 | 9633 | 482 | 214 |
| | 2002 | 38 | 44 | 28 | 1691 | 943 | 736 | 44 | 8495 | 476 | 174 |
| | 2003 | 27 | 40 | 20 | 1143 | 1106 | 737 | 44 | 6608 | 369 | 252 |
| Thistle | 2000 | 48 | 47 | 32 | 1004 | 893 | 1191 | 49 | 12113 | 577 | 580 |
| | 2001 | 48 | 49 | 35 | 883 | 648 | 1439 | 51 | 12021 | 673 | 352 |
| | 2002 | 47 | 43 | 48 | 1180 | 699 | 1262 | 54 | 13144 | 720 | 356 |
| | 2003 | 45 | 34 | 34 | 954 | 687 | 927 | 34 | 9148 | 525 | 258 |
| Toby | 2000 | 30 | 34 | 27 | 481 | 506 | 946 | 35 | 9344 | 364 | 587 |
| | 2001 | 38 | 31 | 25 | 634 | 748 | 1023 | 38 | 10213 | 619 | 151 |
| | 2002 | 47 | 36 | 44 | 1252 | 486 | 1334 | 46 | 12430 | 607 | 242 |
| | 2003 | 40 | 28 | 30 | 885 | 458 | 811 | 39 | 7638 | 512 | 829 |
| Two creek | 2000 | 43 | 36 | 29 | 767 | 810 | 1164 | 44 | 10922 | 635 | 459 |
| | 2001 | 42 | 31 | 27 | 738 | 604 | 858 | 43 | 9799 | 466 | 219 |
| | 2002 | 41 | 40 | 39 | 1221 | 717 | 1007 | 47 | 11330 | 733 | 243 |
| | 2003 | 37 | 32 | 31 | 806 | 716 | 878 | 40 | 9105 | 668 | 278 |
| Willow | 2000 | 34 | 34 | 27 | 845 | 690 | 1053 | 38 | 11151 | 573 | 291 |
| | 2001 | 42 | 30 | 28 | 856 | 624 | 1304 | 43 | 10579 | 755 | 294 |
| | 2002 | 41 | 40 | 33 | 1416 | 696 | 1022 | 46 | 11374 | 749 | 181 |
| | 2003 | 40 | 27 | 28 | 1035 | 699 | 1069 | 35 | 9012 | 670 | 288 |

**Table C-2**: Standard deviation of EVIm based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date | End date | Peak date | Onset value | End value | Peak value | Length | Time-int.VI | Rt of greenup | Rt of senescence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 36 | 42 | 37 | 790 | 973 | 1397 | 46 | 11899 | 1152 | 759 |
| | 2001 | 44 | 32 | 26 | 559 | 477 | 679 | 44 | 9948 | 431 | 241 |
| | 2002 | 34 | 35 | 34 | 1129 | 534 | 881 | 35 | 8377 | 741 | 205 |
| | 2003 | 30 | 30 | 29 | 908 | 565 | 740 | 28 | 7410 | 660 | 412 |
| Burnt pine | 2000 | 22 | 21 | 27 | 857 | 495 | 935 | 32 | 9375 | 880 | 421 |
| | 2001 | 26 | 17 | 25 | 576 | 525 | 510 | 32 | 7553 | 662 | 152 |
| | 2002 | 43 | 32 | 34 | 715 | 746 | 644 | 51 | 10616 | 720 | 199 |
| | 2003 | 40 | 21 | 25 | 742 | 586 | 621 | 42 | 8915 | 712 | 493 |
| Cassidy | 2000 | 27 | 38 | 24 | 694 | 815 | 948 | 39 | 10468 | 821 | 254 |
| | 2001 | 24 | 40 | 26 | 906 | 757 | 1256 | 52 | 12508 | 1495 | 861 |
| | 2002 | 43 | 29 | 40 | 1257 | 599 | 1058 | 51 | 12100 | 988 | 250 |
| | 2003 | 39 | 13 | 31 | 888 | 530 | 996 | 41 | 10676 | 671 | 283 |
| Chickadee | 2000 | 35 | 38 | 28 | 694 | 715 | 1046 | 41 | 9973 | 935 | 494 |
| | 2001 | 28 | 41 | 23 | 894 | 703 | 917 | 44 | 10575 | 1062 | 348 |
| | 2002 | 44 | 41 | 38 | 1266 | 633 | 980 | 46 | 10758 | 856 | 302 |
| | 2003 | 41 | 28 | 33 | 875 | 669 | 784 | 39 | 8606 | 621 | 438 |
| Fireweed | 2000 | 37 | 33 | 23 | 677 | 675 | 721 | 37 | 7351 | 702 | 487 |
| | 2001 | 34 | 44 | 28 | 1432 | 662 | 940 | 39 | 7202 | 944 | 398 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 33 | 36 | 34 | 1471 | 599 | 796 | 39 | 8229 | 812 | 191 |
| | 2003 | 31 | 37 | 28 | 1009 | 922 | 835 | 34 | 5984 | 710 | 403 |
| Goose | 2000 | 45 | 43 | 23 | 900 | 736 | 708 | 31 | 7185 | 707 | 380 |
| | 2001 | 45 | 38 | 23 | 1016 | 722 | 751 | 45 | 7678 | 591 | 303 |
| | 2002 | 38 | 46 | 33 | 1370 | 839 | 894 | 34 | 7791 | 706 | 315 |
| | 2003 | 32 | 43 | 26 | 1114 | 1048 | 685 | 40 | 6167 | 415 | 436 |
| Kashka | 2000 | 37 | 40 | 23 | 708 | 873 | 561 | 50 | 9075 | 337 | 262 |
| | 2001 | 35 | 59 | 25 | 671 | 527 | 912 | 50 | 9945 | 1072 | 399 |
| | 2002 | 47 | 68 | 37 | 1136 | 854 | 915 | 43 | 8319 | 744 | 397 |
| | 2003 | 43 | 39 | 37 | 896 | 665 | 1068 | 42 | 8278 | 1047 | 252 |
| Millions | 2000 | 30 | 44 | 31 | 586 | 520 | 625 | 48 | 10482 | 615 | 502 |
| | 2001 | 26 | 41 | 10 | 714 | 520 | 398 | 47 | 9682 | 678 | 327 |
| | 2002 | 56 | 45 | 49 | 1141 | 433 | 1213 | 47 | 9817 | 893 | 124 |
| | 2003 | 56 | 34 | 39 | 857 | 423 | 991 | 56 | 10937 | 734 | 195 |
| Mosquito | 2000 | 32 | 35 | 21 | 687 | 657 | 596 | 36 | 8670 | 864 | 279 |
| | 2001 | 16 | 36 | 14 | 777 | 645 | 523 | 37 | 9827 | 892 | 362 |
| | 2002 | 48 | 43 | 39 | 1037 | 700 | 753 | 48 | 9992 | 1257 | 173 |
| | 2003 | 37 | 27 | 23 | 1204 | 520 | 830 | 34 | 7273 | 487 | 367 |
| Pierre | 2000 | 38 | 51 | 31 | 610 | 959 | 915 | 46 | 10277 | 915 | 637 |
| | 2001 | 54 | 33 | 34 | 802 | 524 | 864 | 64 | 12720 | 837 | 362 |
| | 2002 | 41 | 35 | 37 | 1644 | 588 | 706 | 40 | 9949 | 572 | 195 |
| | 2003 | 35 | 39 | 37 | 638 | 766 | 1070 | 40 | 8406 | 670 | 1098 |
| Sak A | 2000 | 35 | 35 | 30 | 795 | 686 | 999 | 40 | 10428 | 896 | 458 |
| | 2001 | 33 | 32 | 25 | 851 | 620 | 909 | 38 | 8347 | 767 | 320 |
| | 2002 | 41 | 42 | 39 | 1147 | 638 | 966 | 46 | 10842 | 878 | 259 |
| | 2003 | 34 | 32 | 27 | 1014 | 711 | 756 | 37 | 8133 | 662 | 346 |
| Sak B | 2000 | 17 | 26 | 24 | 777 | 656 | 798 | 30 | 8338 | 446 | 284 |
| | 2001 | 22 | 29 | 24 | 660 | 716 | 711 | 35 | 9654 | 774 | 256 |
| | 2002 | 36 | 40 | 28 | 1671 | 899 | 741 | 39 | 7907 | 751 | 263 |
| | 2003 | 26 | 32 | 20 | 1269 | 1177 | 760 | 38 | 6373 | 591 | 251 |
| Thistle | 2000 | 42 | 44 | 32 | 961 | 745 | 1193 | 40 | 10381 | 840 | 707 |
| | 2001 | 45 | 47 | 34 | 956 | 657 | 1434 | 50 | 11734 | 1093 | 442 |
| | 2002 | 46 | 39 | 48 | 1166 | 694 | 1253 | 50 | 12152 | 1133 | 347 |
| | 2003 | 43 | 32 | 34 | 884 | 624 | 929 | 35 | 9430 | 653 | 331 |
| Toby | 2000 | 26 | 31 | 26 | 565 | 400 | 990 | 37 | 9990 | 749 | 632 |
| | 2001 | 36 | 29 | 25 | 701 | 629 | 1061 | 42 | 10865 | 1033 | 249 |
| | 2002 | 46 | 26 | 44 | 1349 | 546 | 1356 | 49 | 13116 | 1151 | 261 |
| | 2003 | 41 | 27 | 27 | 928 | 805 | 804 | 39 | 7530 | 415 | 844 |
| Two creek | 2000 | 35 | 33 | 29 | 718 | 754 | 1161 | 41 | 10456 | 1002 | 582 |
| | 2001 | 39 | 30 | 26 | 811 | 604 | 853 | 42 | 9725 | 758 | 267 |
| | 2002 | 41 | 34 | 37 | 1355 | 633 | 984 | 44 | 10932 | 935 | 306 |
| | 2003 | 37 | 30 | 31 | 945 | 705 | 856 | 39 | 9175 | 715 | 358 |
| Willow | 2000 | 28 | 31 | 26 | 883 | 665 | 1032 | 34 | 10136 | 925 | 378 |
| | 2001 | 38 | 30 | 27 | 819 | 715 | 1299 | 44 | 10614 | 1355 | 408 |
| | 2002 | 40 | 34 | 32 | 1479 | 618 | 1014 | 42 | 10609 | 1081 | 187 |
| | 2003 | 39 | 26 | 26 | 1330 | 602 | 1028 | 34 | 8833 | 657 | 359 |

**Table C-3**: Standard deviation of NDVIz based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date | End date | Peak date | Onset value | End value | Peak value | Len-gth | Time-int.VI | Rt of greenup | Rt of senescence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 51 | 24 | 39 | 1830 | 1559 | 606 | 48 | 22864 | 281 | 880 |
| | 2001 | 60 | 32 | 37 | 1716 | 2133 | 520 | 70 | 29856 | 384 | 997 |
| | 2002 | 13 | 35 | 34 | 1462 | 1574 | 488 | 34 | 15618 | 414 | 472 |
| | 2003 | 17 | 36 | 21 | 953 | 1999 | 507 | 38 | 17545 | 223 | 296 |
| Burnt pine | 2000 | 53 | 19 | 31 | 1670 | 2031 | 386 | 44 | 20087 | 218 | 594 |
| | 2001 | 37 | 36 | 34 | 1454 | 1671 | 323 | 52 | 23180 | 410 | 878 |
| | 2002 | 16 | 46 | 24 | 1010 | 1612 | 359 | 42 | 17974 | 305 | 361 |
| | 2003 | 13 | 39 | 27 | 951 | 1764 | 325 | 38 | 12677 | 257 | 264 |
| Cassidy | 2000 | 63 | 14 | 28 | 1848 | 1244 | 217 | 51 | 24031 | 226 | 482 |
| | 2001 | 64 | 31 | 41 | 1867 | 1552 | 162 | 71 | 28486 | 434 | 635 |
| | 2002 | 21 | 33 | 43 | 1859 | 1612 | 330 | 39 | 18319 | 354 | 486 |
| | 2003 | 18 | 19 | 24 | 1349 | 1506 | 209 | 29 | 10099 | 244 | 205 |
| Chickadee | 2000 | 58 | 26 | 33 | 2109 | 1890 | 467 | 52 | 22998 | 335 | 549 |
| | 2001 | 47 | 23 | 46 | 1725 | 2037 | 555 | 52 | 21650 | 479 | 1069 |
| | 2002 | 19 | 28 | 30 | 1483 | 1700 | 452 | 32 | 14556 | 378 | 565 |
| | 2003 | 17 | 19 | 28 | 1147 | 1593 | 424 | 27 | 11013 | 277 | 447 |
| Fireweed | 2000 | 41 | 32 | 21 | 1440 | 1281 | 800 | 41 | 16305 | 288 | 357 |
| | 2001 | 60 | 36 | 33 | 1542 | 1721 | 689 | 54 | 20893 | 228 | 1197 |
| | 2002 | 19 | 54 | 20 | 529 | 1643 | 669 | 46 | 17461 | 448 | 274 |
| | 2003 | 22 | 13 | 16 | 1296 | 1299 | 565 | 28 | 8963 | 235 | 171 |
| Goose | 2000 | 38 | 38 | 28 | 1737 | 1515 | 893 | 44 | 21160 | 370 | 553 |
| | 2001 | 59 | 27 | 31 | 2035 | 1559 | 708 | 52 | 19605 | 307 | 728 |
| | 2002 | 15 | 48 | 28 | 1480 | 1800 | 767 | 40 | 19630 | 365 | 645 |
| | 2003 | 17 | 18 | 22 | 1575 | 1944 | 643 | 26 | 13785 | 295 | 311 |
| Kashka | 2000 | 55 | 26 | 29 | 1833 | 1697 | 415 | 54 | 21176 | 269 | 435 |
| | 2001 | 50 | 24 | 57 | 1827 | 2053 | 420 | 50 | 18845 | 454 | 1599 |
| | 2002 | 18 | 22 | 33 | 701 | 1883 | 441 | 32 | 13484 | 297 | 886 |
| | 2003 | 15 | 15 | 26 | 1182 | 1254 | 305 | 20 | 11180 | 223 | 513 |
| Millions | 2000 | 40 | 5 | 40 | 1901 | 1450 | 279 | 44 | 20896 | 310 | 468 |
| | 2001 | 43 | 3 | 45 | 1351 | 1858 | 393 | 50 | 20842 | 402 | 863 |
| | 2002 | 29 | 9 | 48 | 1548 | 1208 | 317 | 27 | 11729 | 554 | 504 |
| | 2003 | 15 | 8 | 32 | 911 | 1128 | 249 | 16 | 6089 | 235 | 486 |
| Mosquito | 2000 | 44 | 21 | 29 | 2327 | 1415 | 537 | 46 | 21930 | 310 | 294 |
| | 2001 | 44 | 21 | 30 | 2491 | 2054 | 569 | 55 | 22992 | 421 | 274 |
| | 2002 | 25 | 36 | 33 | 1913 | 2433 | 765 | 39 | 20479 | 367 | 363 |
| | 2003 | 19 | 19 | 27 | 1635 | 1772 | 624 | 31 | 16175 | 252 | 406 |
| Pierre | 2000 | 61 | 20 | 33 | 1554 | 1543 | 755 | 53 | 26347 | 248 | 452 |
| | 2001 | 58 | 24 | 53 | 1954 | 2110 | 646 | 58 | 21579 | 299 | 901 |
| | 2002 | 17 | 42 | 23 | 1476 | 1273 | 462 | 36 | 15099 | 352 | 333 |
| | 2003 | 18 | 12 | 20 | 1258 | 1478 | 470 | 24 | 9065 | 166 | 458 |
| Sak A | 2000 | 48 | 30 | 32 | 1926 | 1793 | 775 | 50 | 24407 | 337 | 519 |
| | 2001 | 61 | 30 | 40 | 1773 | 2002 | 685 | 58 | 25036 | 326 | 1058 |
| | 2002 | 20 | 36 | 29 | 1554 | 1756 | 655 | 35 | 17783 | 392 | 577 |
| | 2003 | 16 | 24 | 25 | 1237 | 2102 | 680 | 29 | 15671 | 289 | 359 |
| Sak B | 2000 | 22 | 28 | 21 | 1439 | 1796 | 408 | 36 | 14530 | 252 | 269 |
| | 2001 | 48 | 38 | 36 | 1715 | 1865 | 571 | 54 | 21631 | 326 | 1528 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 12 | 24 | 34 | 668 | 1737 | 794 | 27 | 13975 | 334 | 1160 |
| | 2003 | 23 | 20 | 19 | 1373 | 2035 | 645 | 31 | 11071 | 231 | 237 |
| Thistle | 2000 | 39 | 23 | 43 | 2070 | 1573 | 577 | 42 | 21480 | 372 | 696 |
| | 2001 | 52 | 24 | 49 | 1953 | 2003 | 702 | 53 | 24696 | 454 | 1187 |
| | 2002 | 15 | 25 | 35 | 1905 | 2070 | 691 | 30 | 15335 | 413 | 693 |
| | 2003 | 19 | 16 | 29 | 1261 | 1401 | 525 | 27 | 13488 | 369 | 381 |
| Toby | 2000 | 41 | 27 | 38 | 1879 | 2192 | 704 | 51 | 21699 | 458 | 314 |
| | 2001 | 44 | 27 | 54 | 1504 | 2151 | 512 | 49 | 19822 | 361 | 935 |
| | 2002 | 14 | 46 | 18 | 1404 | 1321 | 362 | 34 | 13724 | 323 | 166 |
| | 2003 | 16 | 13 | 25 | 1295 | 1048 | 370 | 21 | 6694 | 215 | 314 |
| Two creek | 2000 | 55 | 28 | 30 | 2034 | 1873 | 488 | 49 | 21634 | 333 | 538 |
| | 2001 | 54 | 21 | 40 | 1888 | 2205 | 495 | 52 | 22690 | 356 | 1069 |
| | 2002 | 19 | 28 | 23 | 1542 | 1851 | 398 | 32 | 14183 | 341 | 338 |
| | 2003 | 16 | 20 | 28 | 1261 | 1617 | 458 | 24 | 12045 | 316 | 378 |
| Willow | 2000 | 53 | 28 | 30 | 2128 | 1719 | 576 | 47 | 21152 | 299 | 412 |
| | 2001 | 57 | 28 | 35 | 2136 | 2006 | 521 | 54 | 23087 | 349 | 913 |
| | 2002 | 18 | 35 | 33 | 1640 | 2155 | 658 | 40 | 17241 | 465 | 622 |
| | 2003 | 19 | 22 | 21 | 1343 | 1615 | 503 | 34 | 14967 | 247 | 254 |

**Table C-4**: Standard deviation of NDVIm based VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Year | Onset date | End date | Peak date | Onset value | End value | Peak value | Len-gth | Time-int.VI | Rt of greenup | Rt of senescence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 2000 | 47 | 22 | 40 | 1301 | 1149 | 603 | 49 | 24351 | 358 | 917 |
| | 2001 | 55 | 20 | 40 | 1658 | 2015 | 517 | 59 | 25286 | 309 | 1248 |
| | 2002 | 9 | 32 | 34 | 1666 | 1492 | 511 | 27 | 14301 | 423 | 506 |
| | 2003 | 14 | 23 | 21 | 1057 | 1690 | 521 | 28 | 13314 | 248 | 261 |
| Burnt pine | 2000 | 37 | 13 | 31 | 1240 | 1843 | 388 | 38 | 17462 | 335 | 588 |
| | 2001 | 32 | 27 | 43 | 1506 | 1865 | 319 | 50 | 22413 | 314 | 1117 |
| | 2002 | 13 | 30 | 24 | 1573 | 1318 | 347 | 31 | 13205 | 268 | 343 |
| | 2003 | 11 | 25 | 27 | 1390 | 1394 | 320 | 27 | 7466 | 291 | 284 |
| Cassidy | 2000 | 43 | 7 | 29 | 1375 | 1188 | 230 | 35 | 16734 | 205 | 492 |
| | 2001 | 59 | 20 | 43 | 1738 | 2006 | 156 | 60 | 22990 | 494 | 698 |
| | 2002 | 21 | 22 | 42 | 2100 | 1692 | 335 | 36 | 16317 | 437 | 499 |
| | 2003 | 15 | 15 | 24 | 1374 | 1499 | 209 | 23 | 9034 | 301 | 226 |
| Chickadee | 2000 | 48 | 18 | 33 | 1546 | 1590 | 455 | 45 | 20818 | 376 | 529 |
| | 2001 | 40 | 18 | 49 | 1619 | 2009 | 561 | 45 | 19449 | 720 | 1163 |
| | 2002 | 15 | 19 | 32 | 1704 | 1547 | 464 | 24 | 12408 | 476 | 677 |
| | 2003 | 13 | 13 | 28 | 1317 | 1465 | 425 | 18 | 9514 | 344 | 460 |
| Fireweed | 2000 | 35 | 26 | 21 | 992 | 1163 | 804 | 39 | 16277 | 379 | 345 |
| | 2001 | 54 | 33 | 32 | 1345 | 1737 | 707 | 49 | 19788 | 208 | 1109 |
| | 2002 | 14 | 32 | 22 | 604 | 1541 | 651 | 27 | 12421 | 367 | 337 |
| | 2003 | 23 | 8 | 16 | 2077 | 1146 | 565 | 25 | 8369 | 234 | 171 |
| Goose | 2000 | 29 | 32 | 28 | 1346 | 1352 | 880 | 41 | 21165 | 481 | 578 |
| | 2001 | 43 | 24 | 32 | 1920 | 1506 | 732 | 40 | 17818 | 312 | 791 |
| | 2002 | 11 | 36 | 29 | 1751 | 1720 | 784 | 31 | 17206 | 378 | 756 |
| | 2003 | 17 | 13 | 22 | 1822 | 1840 | 642 | 22 | 13234 | 321 | 335 |
| Kashka | 2000 | 50 | 13 | 29 | 1662 | 1396 | 386 | 49 | 20853 | 281 | 425 |
| | 2001 | 42 | 20 | 62 | 1715 | 2043 | 432 | 47 | 17559 | 752 | 1827 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 12 | 14 | 34 | 943 | 1736 | 452 | 18 | 10244 | 325 | 898 |
| | 2003 | 12 | 10 | 26 | 1401 | 1071 | 305 | 14 | 9509 | 254 | 496 |
| Millions | 2000 | 34 | 3 | 40 | 603 | 1204 | 276 | 36 | 17975 | 222 | 449 |
| | 2001 | 43 | 3 | 45 | 1275 | 1751 | 380 | 48 | 20098 | 448 | 852 |
| | 2002 | 29 | 7 | 47 | 1504 | 1086 | 315 | 28 | 11725 | 347 | 486 |
| | 2003 | 11 | 5 | 32 | 1141 | 1128 | 249 | 11 | 5063 | 261 | 484 |
| Mosquito | 2000 | 30 | 19 | 29 | 2142 | 1163 | 530 | 33 | 19047 | 348 | 287 |
| | 2001 | 37 | 19 | 35 | 2495 | 1892 | 550 | 50 | 22575 | 459 | 494 |
| | 2002 | 26 | 22 | 33 | 2040 | 2099 | 745 | 33 | 20149 | 404 | 337 |
| | 2003 | 14 | 11 | 27 | 1887 | 1663 | 624 | 16 | 14052 | 301 | 405 |
| Pierre | 2000 | 48 | 15 | 37 | 1327 | 1278 | 755 | 40 | 21742 | 342 | 589 |
| | 2001 | 52 | 20 | 55 | 1856 | 2264 | 669 | 52 | 20254 | 340 | 1078 |
| | 2002 | 12 | 33 | 23 | 1862 | 1175 | 442 | 32 | 13998 | 310 | 370 |
| | 2003 | 16 | 9 | 21 | 1170 | 1226 | 470 | 20 | 8284 | 162 | 422 |
| Sak A | 2000 | 40 | 24 | 31 | 1495 | 1486 | 771 | 46 | 23590 | 398 | 488 |
| | 2001 | 53 | 24 | 42 | 1643 | 1918 | 693 | 50 | 22772 | 401 | 1106 |
| | 2002 | 16 | 27 | 30 | 1810 | 1663 | 684 | 25 | 15532 | 484 | 652 |
| | 2003 | 14 | 16 | 25 | 1533 | 1836 | 678 | 22 | 13578 | 312 | 373 |
| Sak B | 2000 | 18 | 19 | 21 | 1170 | 1638 | 405 | 28 | 12350 | 355 | 254 |
| | 2001 | 39 | 31 | 37 | 1556 | 1994 | 597 | 49 | 19906 | 365 | 1571 |
| | 2002 | 10 | 16 | 34 | 1299 | 1598 | 805 | 21 | 12717 | 410 | 1142 |
| | 2003 | 18 | 12 | 19 | 1514 | 1543 | 645 | 20 | 9569 | 291 | 233 |
| Thistle | 2000 | 33 | 21 | 43 | 1786 | 1379 | 573 | 36 | 19666 | 419 | 733 |
| | 2001 | 48 | 17 | 52 | 1983 | 1944 | 635 | 47 | 22977 | 460 | 1269 |
| | 2002 | 12 | 17 | 36 | 1944 | 1946 | 693 | 21 | 13717 | 455 | 701 |
| | 2003 | 16 | 11 | 29 | 1481 | 1306 | 525 | 19 | 11705 | 606 | 381 |
| Toby | 2000 | 26 | 12 | 38 | 1171 | 1702 | 728 | 32 | 15084 | 747 | 479 |
| | 2001 | 37 | 23 | 55 | 1436 | 2080 | 534 | 45 | 18490 | 582 | 932 |
| | 2002 | 10 | 39 | 18 | 1646 | 1253 | 334 | 30 | 10615 | 307 | 162 |
| | 2003 | 13 | 9 | 25 | 1494 | 1048 | 370 | 17 | 6100 | 246 | 307 |
| Two creek | 2000 | 46 | 22 | 31 | 1681 | 1641 | 478 | 43 | 19505 | 427 | 560 |
| | 2001 | 49 | 16 | 42 | 1801 | 2068 | 504 | 47 | 21270 | 400 | 1160 |
| | 2002 | 15 | 19 | 24 | 1715 | 1691 | 402 | 23 | 11973 | 391 | 378 |
| | 2003 | 14 | 13 | 28 | 1371 | 1504 | 459 | 19 | 10753 | 375 | 371 |
| Willow | 2000 | 36 | 24 | 28 | 1640 | 1686 | 555 | 38 | 18211 | 357 | 393 |
| | 2001 | 50 | 20 | 37 | 2011 | 1916 | 534 | 50 | 21552 | 377 | 1056 |
| | 2002 | 15 | 22 | 34 | 1614 | 1968 | 652 | 27 | 13691 | 592 | 612 |
| | 2003 | 16 | 16 | 21 | 1515 | 1523 | 507 | 26 | 13082 | 336 | 278 |

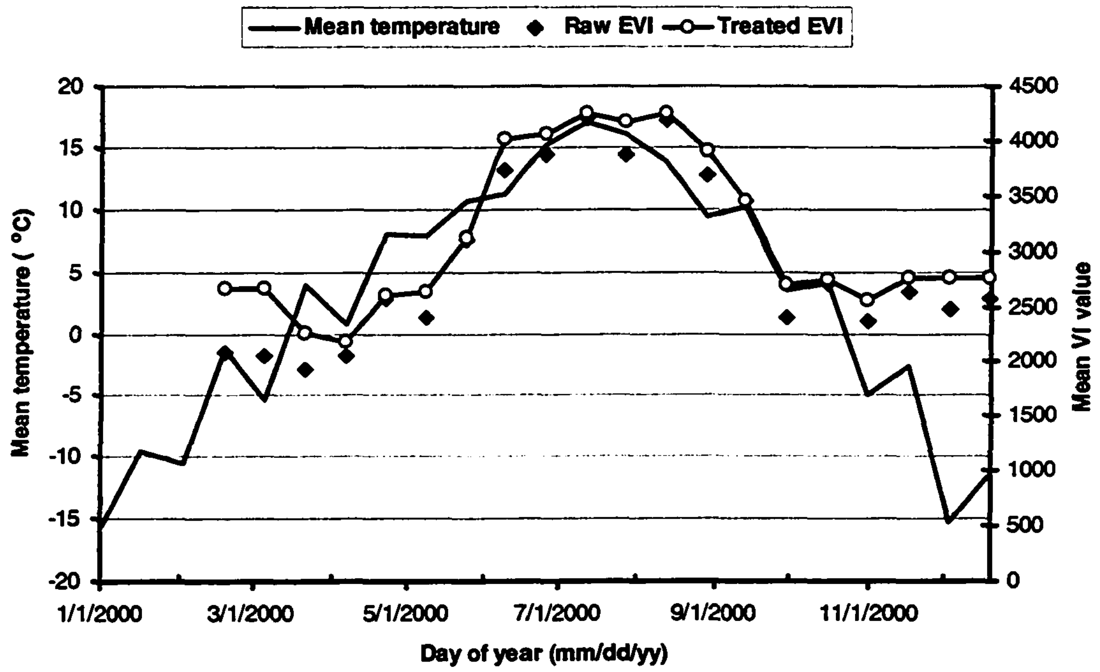


**Figure C-1:** Time series plot of mean temperature and EVI for the FORWARD study area in 2000.

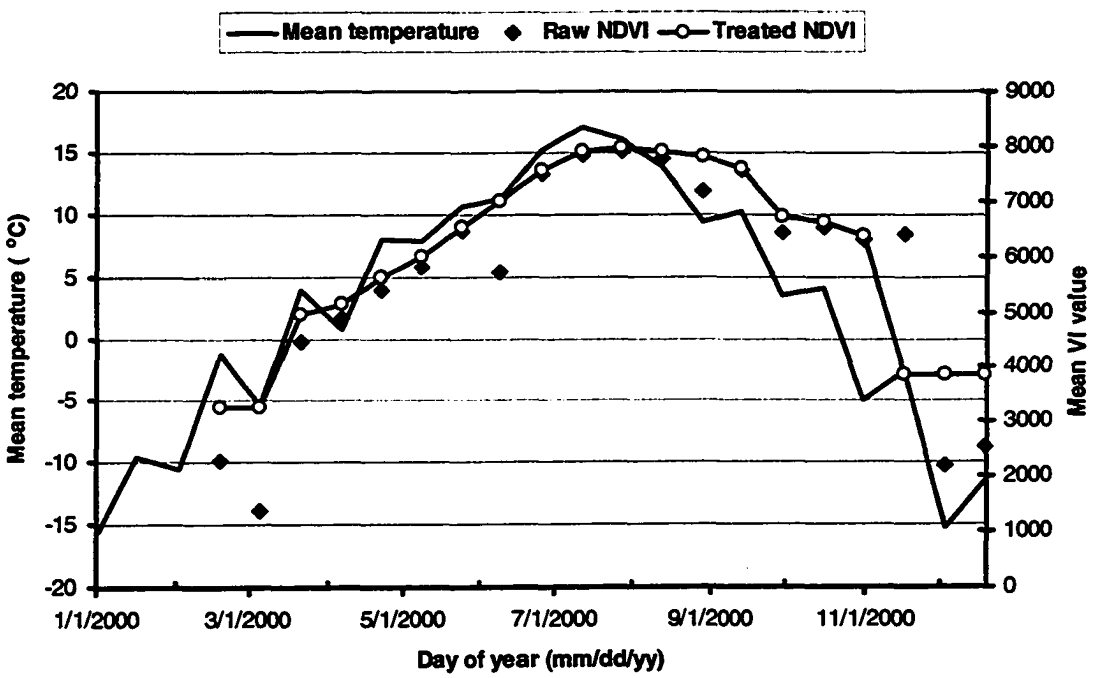


**Figure C-2:** Time series plot of mean temperature and NDVI for the FORWARD study area in 2000.

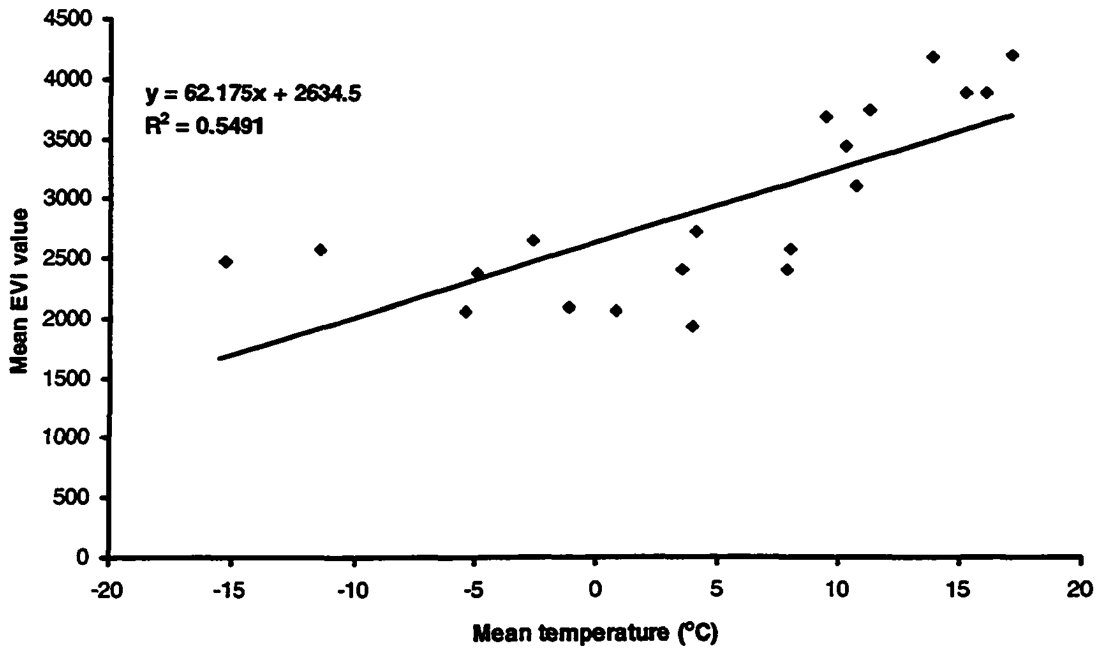


**Figure C-3:** Mean temperature versus mean EVI for the FORWARD study area in 2000.

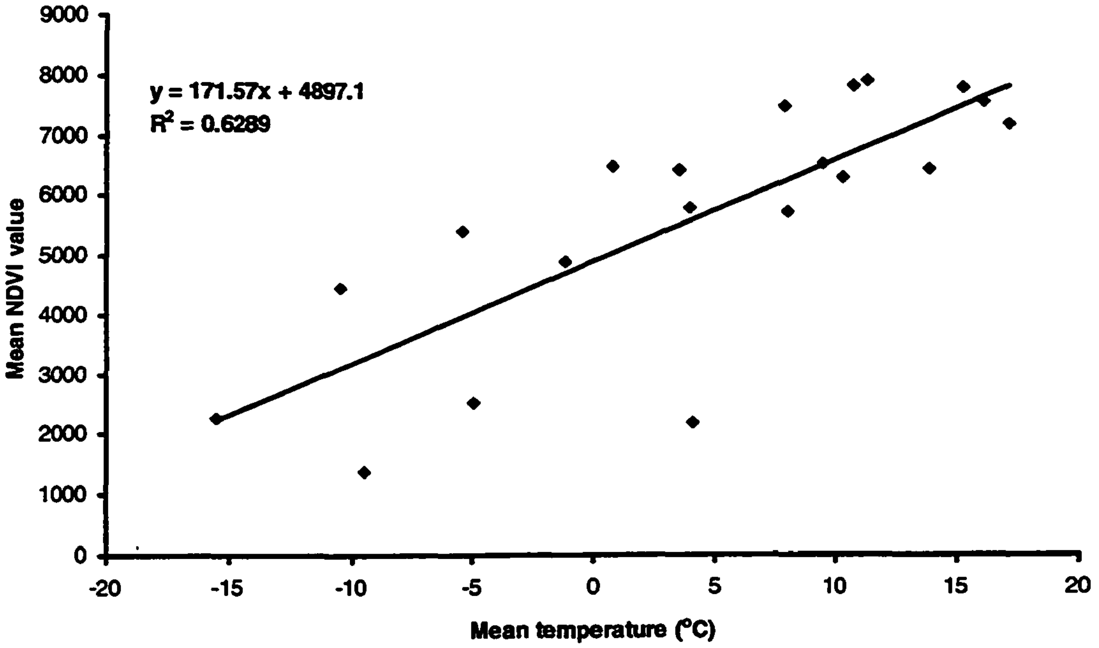


**Figure C-4:** Mean temperature versus mean NDVI for the FORWARD study area in 2000.

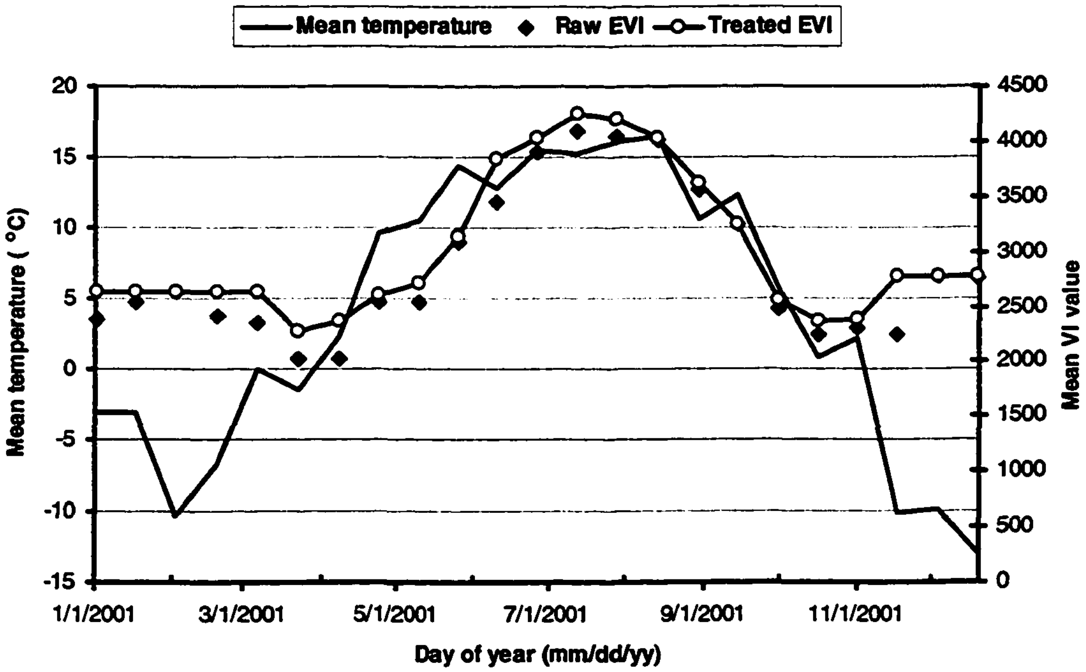


**Figure C-5:** Time series plot of mean temperature and EVI for the FORWARD study area in 2001.

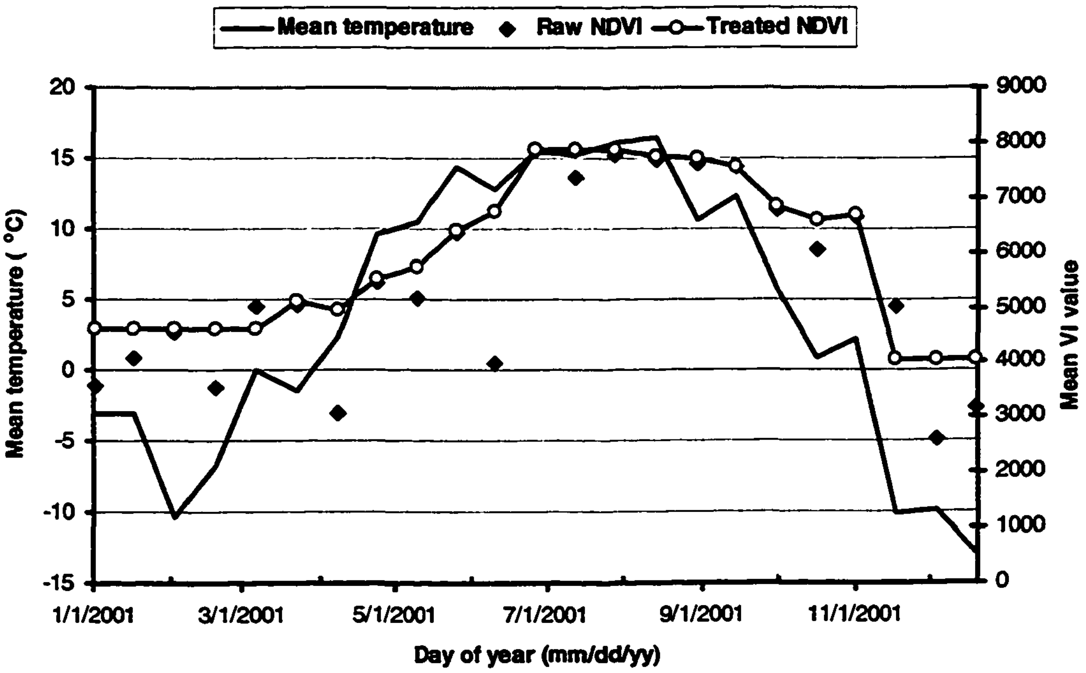


**Figure C-6:** Time series plot of mean temperature and NDVI for the FORWARD study area in 2001.

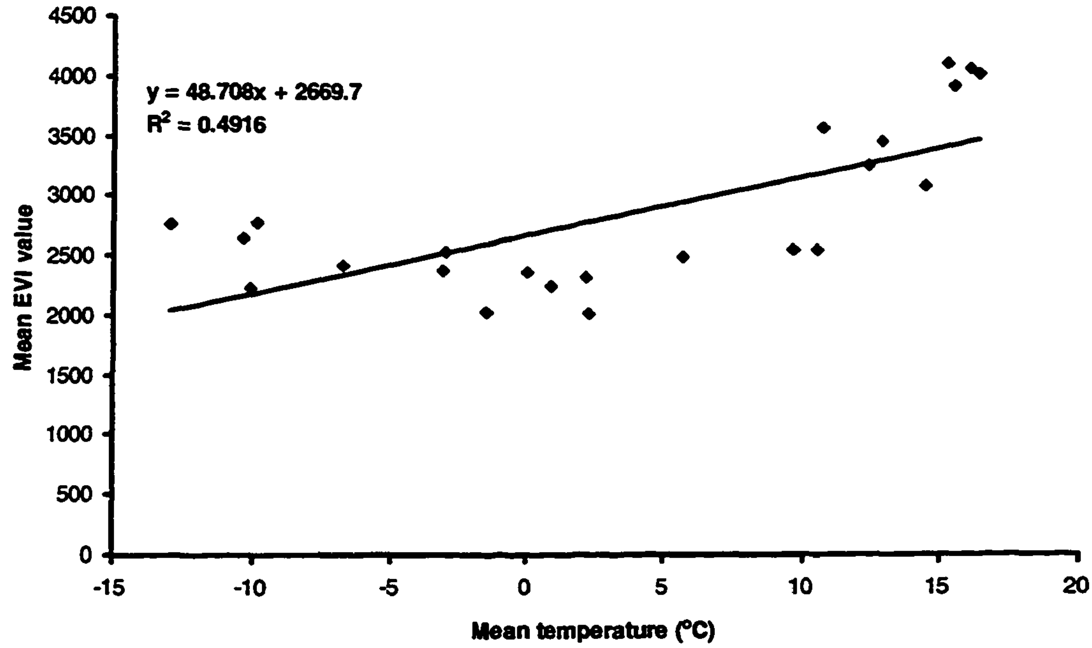


**Figure C-7**: Mean temperature versus mean EVI for the FORWARD study area in 2001.

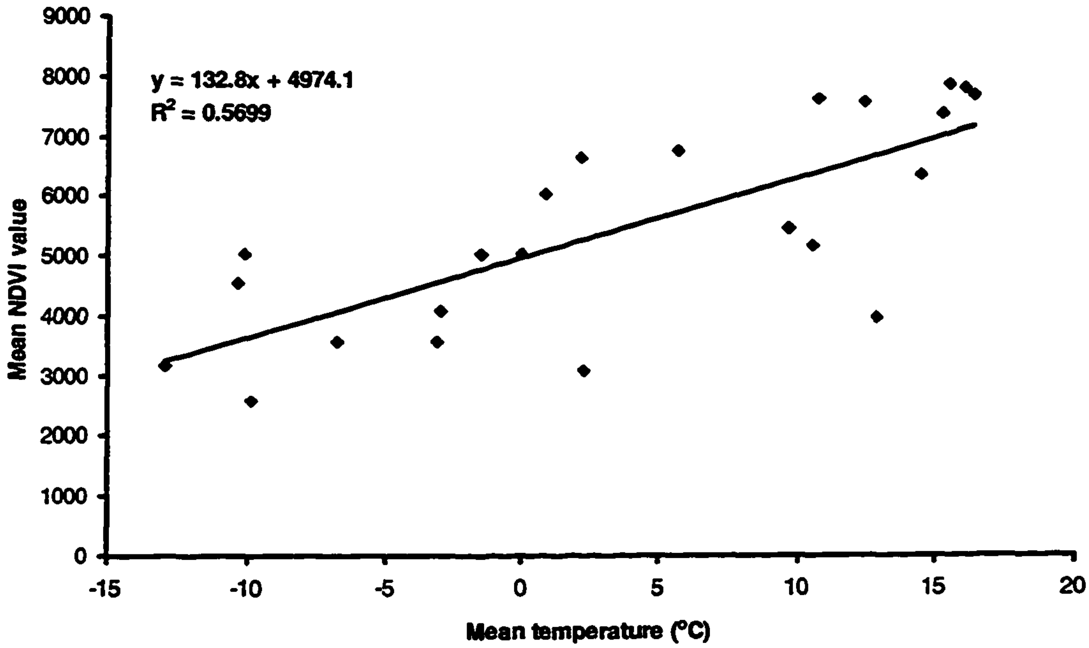


**Figure C-8**: Mean temperature versus mean NDVI for the FORWARD study area in 2001.

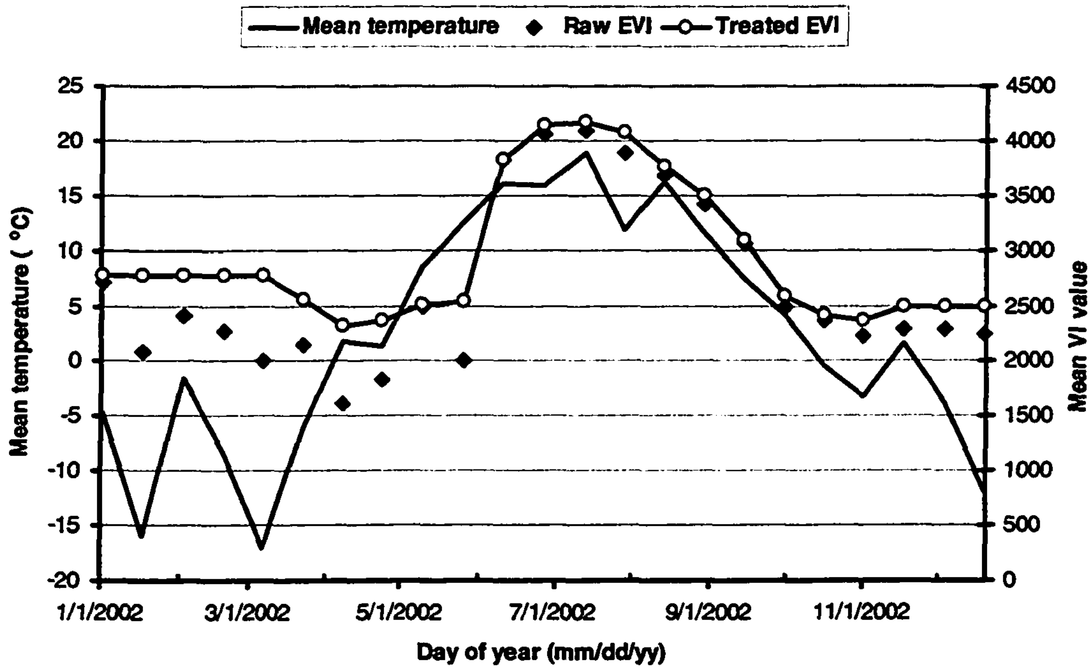


**Figure C-9**: Time series plot of mean temperature and EVI for the FORWARD study area in 2002.

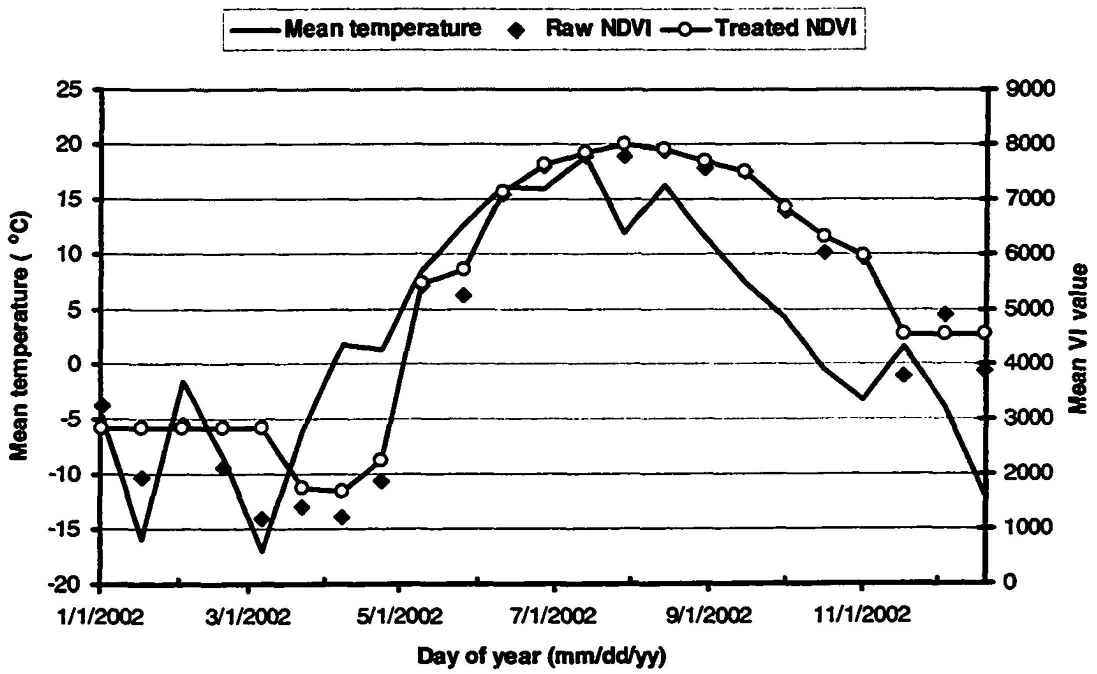


**Figure 5-10**: Time series plot of mean temperature and NDVI for the FORWARD study area in 2002.

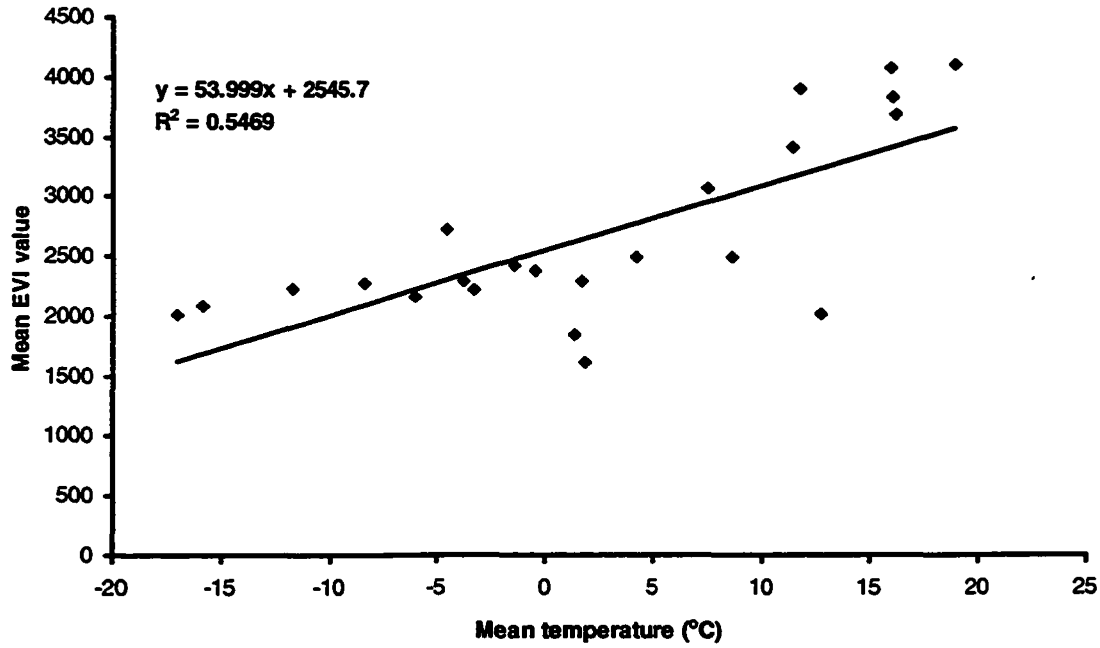


**Figure C-11**: Mean temperature versus mean EVI for the FORWARD study area in 2002.

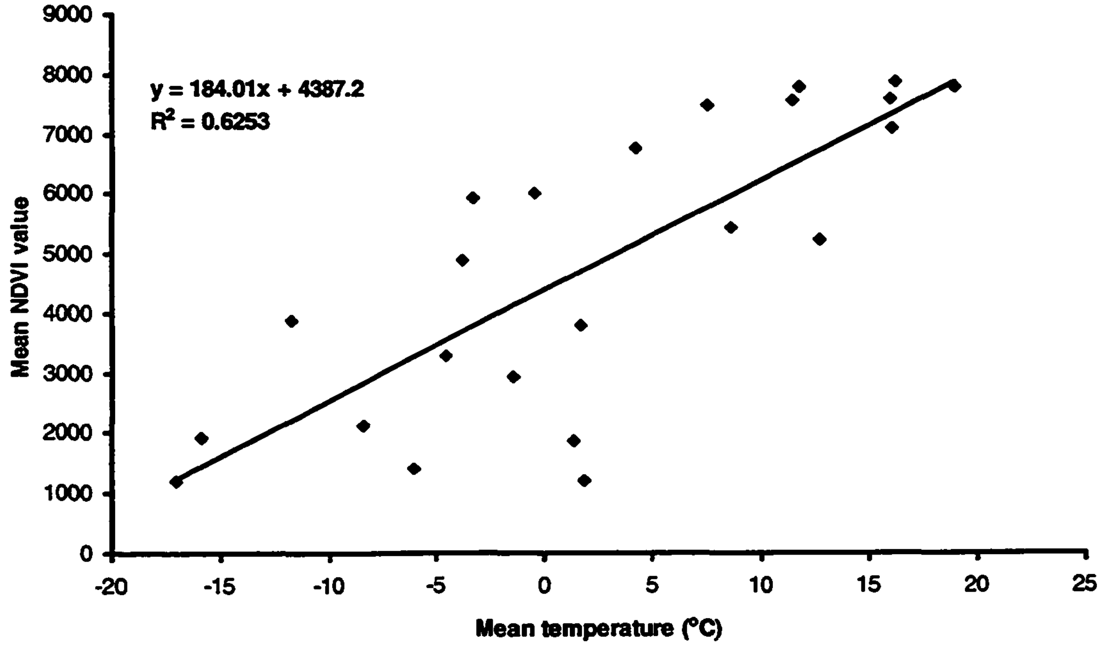


**Figure C-12**: Mean temperature versus mean NDVI for the FORWARD study area in 2002.

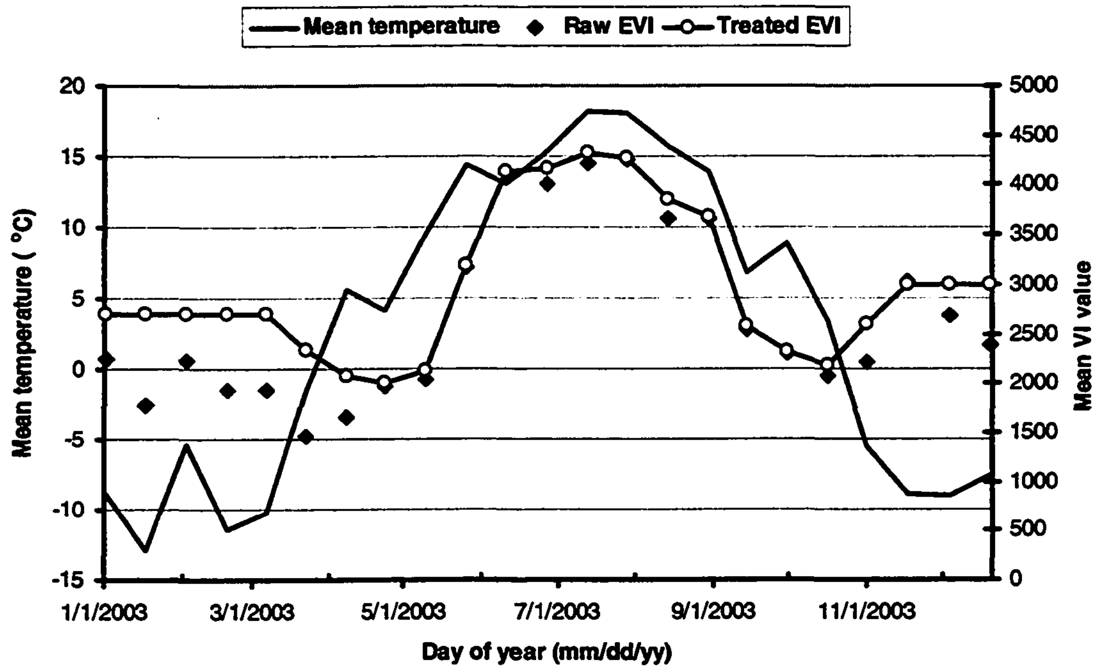


**Figure C-13**: Time series plot of mean temperature and EVI for the FORWARD study area in 2003.

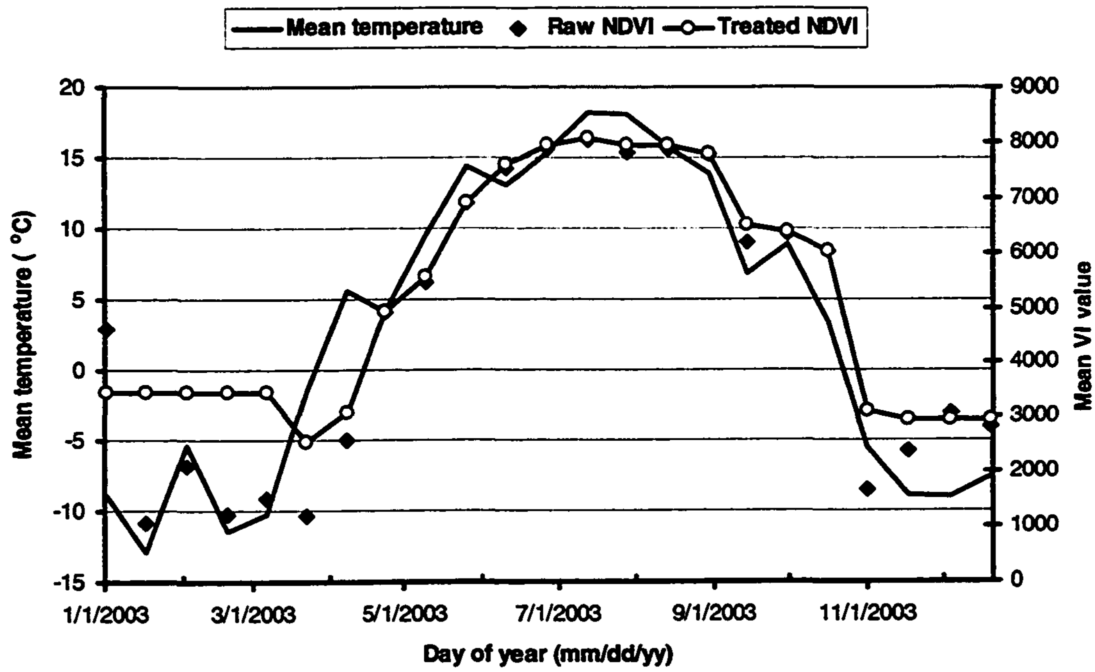


**Figure C-14**: Time series plot of mean temperature and NDVI for the FORWARD study area in 2003.

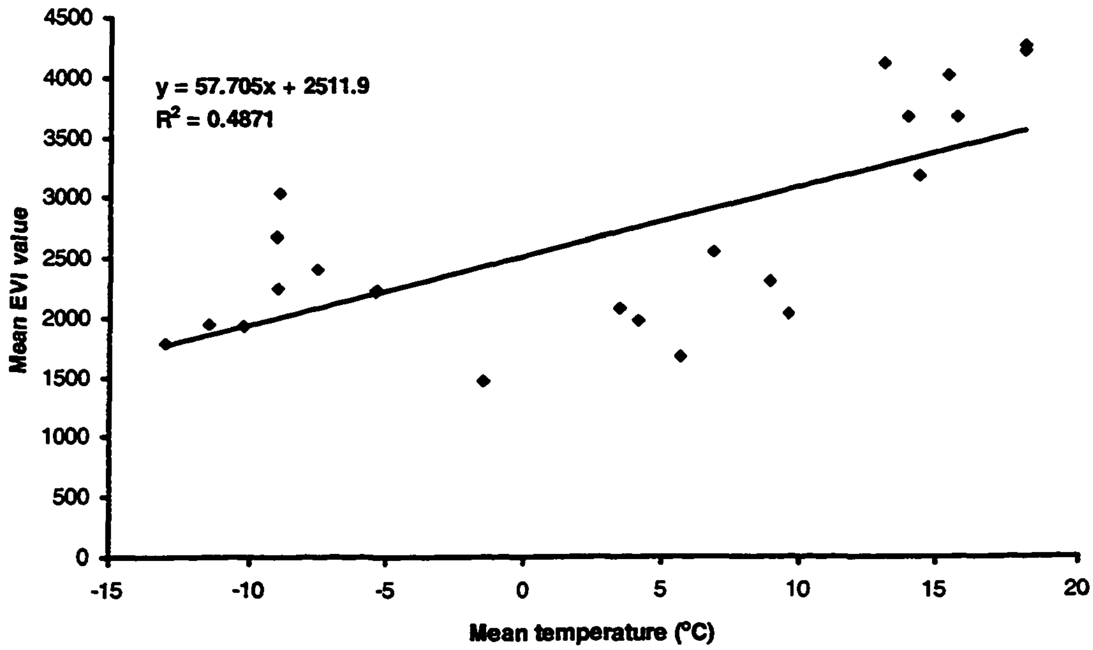


**Figure C-15:** Mean temperature versus mean EVI for the FORWARD study area in 2003.

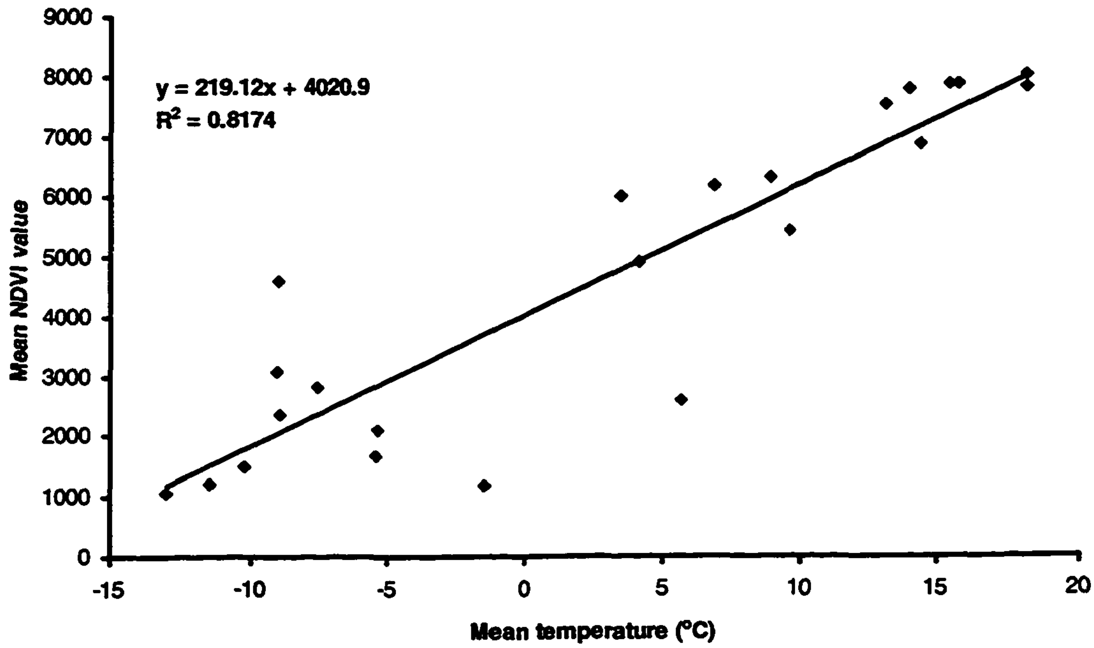


**Figure C-16:** Mean temperature versus mean NDVI for the FORWARD study area in 2003.

**Table C-5**: Difference between zeroes excluded and zeroes included mean EVIm VPMs for 2000-2003 for 16 watersheds.

| Watersheds | Onset date | End date | Peak date | Onset value | End value | Peak value | Length | Time-int.VI | Rt of greenup | Rt of senescence |
|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 0 | 2 | 27 | 0 | 28 | 738 | 2 | 4750 | 29 | 102 |
| | 11 | 9 | 51 | 266 | 95 | 1044 | -3 | 9009 | 39 | 101 |
| | 6 | 6 | 36 | 162 | 71 | 966 | 0 | 7857 | 60 | 76 |
| | 12 | 12 | 42 | 246 | 145 | 1139 | 0 | 7638 | 164 | 115 |
| Burnt pine | 2 | 3 | 8 | 38 | 33 | 231 | 1 | 1768 | 24 | 23 |
| | 3 | 7 | 10 | 68 | 77 | 259 | 4 | 2178 | 28 | 25 |
| | 12 | 0 | 26 | 300 | 0 | 681 | -12 | 5940 | 70 | 53 |
| | 1 | 18 | 16 | 15 | 198 | 489 | 17 | 3552 | 88 | 48 |
| Cassidy | 0 | 0 | 17 | 0 | 0 | 514 | 0 | 3703 | 7 | 48 |
| | 0 | 0 | 18 | 25 | 0 | 552 | 0 | 3395 | 49 | 78 |
| | 0 | 0 | 30 | 0 | 0 | 848 | 0 | 7674 | 6 | 73 |
| | 0 | 0 | 11 | 62 | 40 | 307 | 0 | 2258 | 27 | 35 |
| Chickadee | 0 | 0 | 25 | 55 | 66 | 649 | 0 | 4816 | 49 | 66 |
| | 0 | 0 | 32 | 106 | 87 | 903 | 0 | 6228 | 101 | 89 |
| | 0 | 0 | 44 | 289 | 86 | 1133 | 0 | 9136 | 104 | 99 |
| | 0 | 0 | 34 | 148 | 153 | 840 | 0 | 6331 | 77 | 98 |
| Fireweed | 0 | 0 | 80 | 638 | 598 | 1613 | 0 | 10305 | 215 | 217 |
| | 0 | 0 | 54 | 314 | 288 | 1263 | 0 | 8859 | 156 | 150 |
| | 0 | 0 | 73 | 824 | 399 | 1560 | 0 | 11867 | 224 | 158 |
| | 0 | 0 | 70 | 564 | 442 | 1526 | 0 | 10544 | 171 | 188 |
| Goose | 0 | 0 | 105 | 943 | 926 | 2144 | 0 | 14447 | 346 | 243 |
| | 0 | 0 | 75 | 572 | 535 | 1544 | 0 | 10847 | 190 | 182 |
| | 0 | 0 | 84 | 909 | 562 | 1823 | 0 | 12969 | 274 | 190 |
| | 0 | 0 | 74 | 755 | 601 | 1523 | 0 | 10847 | 185 | 195 |
| Kashka | 0 | 0 | 45 | 303 | 219 | 916 | 0 | 6934 | 86 | 87 |
| | 0 | 0 | 29 | 84 | 119 | 723 | 0 | 4851 | 110 | 80 |
| | 0 | 0 | 71 | 610 | 282 | 1646 | 0 | 11905 | 231 | 153 |
| | 0 | 0 | 63 | 209 | 444 | 1507 | 0 | 10385 | 243 | 160 |
| Millions | 0 | 0 | 19 | 0 | 0 | 469 | 0 | 3389 | 19 | 45 |
| | 0 | 0 | 47 | 0 | 92 | 1288 | 0 | 7446 | 113 | 138 |
| | 0 | 0 | 54 | 201 | 0 | 1451 | 0 | 11120 | 88 | 81 |
| | 0 | 0 | 48 | 285 | 82 | 1147 | 0 | 8493 | 85 | 86 |
| Mosquito | 0 | 0 | 18 | 173 | 100 | 521 | 0 | 3915 | 65 | 46 |
| | 0 | 0 | 17 | 109 | 0 | 519 | 0 | 3408 | 58 | 54 |
| | 0 | 0 | 27 | 236 | 178 | 766 | 0 | 6508 | 106 | 58 |
| | 0 | 0 | 22 | 128 | 83 | 534 | 0 | 3842 | 48 | 69 |
| Pierre | 0 | 0 | 50 | 200 | 298 | 1049 | 0 | 7445 | 106 | 133 |
| | 0 | 0 | 55 | 197 | 115 | 1188 | 0 | 8457 | 68 | 133 |
| | 0 | 0 | 86 | 562 | 78 | 1867 | 0 | 14828 | 111 | 154 |
| | 0 | 0 | 35 | 119 | 164 | 833 | 0 | 6179 | 66 | 111 |
| Sak A | 0 | 0 | 38 | 264 | 256 | 930 | 0 | 6856 | 111 | 102 |
| | 0 | 0 | 39 | 287 | 216 | 891 | 0 | 6745 | 91 | 93 |
| | 0 | 0 | 47 | 465 | 232 | 1180 | 0 | 9660 | 127 | 109 |
| | 0 | 0 | 41 | 348 | 300 | 1024 | 0 | 7389 | 141 | 108 |
| Sak B | 0 | 0 | 13 | 33 | 71 | 321 | 0 | 2584 | 28 | 36 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 8 | 73 | 17 | 221 | 0 | 1604 | 40 | 22 |
| | 0 | 0 | 54 | 286 | 163 | 1321 | 0 | 10250 | 139 | 121 |
| | 0 | 0 | 42 | 66 | 445 | 1052 | 0 | 7751 | 97 | 139 |
| Thistle | 0 | 0 | 47 | 235 | 142 | 1151 | 0 | 8087 | 113 | 135 |
| | 0 | 0 | 73 | 441 | 336 | 1786 | 0 | 12423 | 188 | 199 |
| | 0 | 0 | 67 | 486 | 364 | 1674 | 0 | 13295 | 175 | 170 |
| | 0 | 0 | 79 | 529 | 255 | 1869 | 0 | 12950 | 242 | 211 |
| Toby | 0 | 0 | 16 | 86 | 143 | 391 | 0 | 2836 | 38 | 49 |
| | 0 | 0 | 32 | 203 | 168 | 844 | 0 | 5775 | 111 | 73 |
| | 0 | 0 | 53 | 301 | 41 | 1451 | 0 | 11583 | 74 | 142 |
| | 0 | 0 | 42 | 89 | 324 | 993 | 0 | 7391 | 84 | 127 |
| Two creek | 3 | 7 | 26 | 56 | 83 | 653 | 4 | 4719 | 46 | 80 |
| | 6 | 12 | 35 | 136 | 125 | 822 | 6 | 6280 | 60 | 80 |
| | 9 | 4 | 38 | 218 | 43 | 967 | -5 | 7641 | 70 | 93 |
| | 6 | 10 | 26 | 125 | 111 | 677 | 4 | 4983 | 78 | 70 |
| Willow | 0 | 0 | 21 | 65 | 114 | 568 | 0 | 4213 | 63 | 56 |
| | 0 | 0 | 28 | 124 | 57 | 741 | 0 | 5469 | 83 | 75 |
| | 0 | 0 | 57 | 479 | 132 | 1643 | 0 | 13550 | 169 | 131 |
| | 0 | 0 | 45 | 254 | 204 | 1137 | 0 | 8395 | 110 | 152 |

**Table C-6: Difference between zeroes excluded and zeroes included mean NDVIm VPMs for 2000-2003 for 16 watersheds.**

| Watersheds | Onset date | End date | Peak date | Onset value | End value | Peak value | Length | Time-int.VI | Rt of greenup | Rt of senescence |
|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 0 | 0 | 12 | 0 | 0 | 430 | 0 | 4953 | 3 | 51 |
| | 2 | 0 | 31 | 107 | 0 | 1079 | -2 | 12862 | 6 | 135 |
| | 0 | 0 | 24 | 0 | 0 | 861 | 0 | 9463 | 0 | 61 |
| | 0 | 0 | 2 | 0 | 0 | 72 | 0 | 818 | 0 | 5 |
| Burnt pine | 0 | 0 | 18 | 0 | 0 | 730 | 0 | 8243 | 0 | 59 |
| | 0 | 0 | 15 | 0 | 0 | 622 | 0 | 7701 | 3 | 49 |
| | 0 | 0 | 5 | 0 | 0 | 190 | 0 | 2042 | 0 | 11 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cassidy | 0 | 0 | 16 | 0 | 0 | 642 | 0 | 7406 | 0 | 60 |
| | 0 | 0 | 55 | 721 | 0 | 2127 | 0 | 23725 | 54 | 179 |
| | 0 | 0 | 7 | 0 | 0 | 253 | 0 | 2865 | 0 | 18 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Chickadee | 0 | 0 | 20 | 35 | 4 | 715 | 0 | 7807 | 2 | 70 |
| | 0 | 0 | 21 | 62 | 0 | 854 | 0 | 9869 | 8 | 92 |
| | 0 | 0 | 10 | 18 | 0 | 340 | 0 | 3691 | 1 | 28 |
| | 0 | 0 | 1 | 16 | 4 | 35 | 0 | 393 | 0 | 3 |
| Fireweed | 0 | 0 | 6 | 0 | 0 | 200 | 0 | 1616 | 5 | 18 |
| | 0 | 0 | 30 | 0 | 0 | 1076 | 0 | 11562 | 0 | 105 |
| | 0 | 0 | 29 | 141 | 0 | 932 | 0 | 8789 | 25 | 76 |
| | 0 | 0 | 0 | 1128 | 59 | 0 | 0 | 0 | 0 | 0 |
| Goose | 0 | 0 | 15 | 47 | 53 | 472 | 0 | 4585 | 10 | 42 |
| | 0 | 0 | 19 | 48 | 13 | 636 | 0 | 6854 | 7 | 61 |
| | 0 | 0 | 23 | 602 | 21 | 751 | 0 | 7143 | 52 | 67 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 3 | 839 | 104 | 105 | 0 | 1064 | 2 | 13 |
| Kashka | 0 | 0 | 21 | 0 | 0 | 721 | 0 | 7105 | 0 | 78 |
| | 0 | 0 | 37 | 112 | 0 | 1412 | 0 | 15825 | 15 | 244 |
| | 0 | 0 | 14 | 0 | 0 | 471 | 0 | 5243 | 0 | 53 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Millions | 0 | 0 | 3 | 0 | 0 | 118 | 0 | 1576 | 0 | 13 |
| | 0 | 0 | 31 | 564 | 0 | 1402 | 0 | 17928 | 43 | 106 |
| | 0 | 0 | 7 | 0 | 0 | 235 | 0 | 2941 | 0 | 18 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mosquito | 0 | 0 | 6 | 133 | 0 | 205 | 0 | 2319 | 0 | 19 |
| | 0 | 0 | 5 | 187 | 0 | 205 | 0 | 2288 | 15 | 15 |
| | 0 | 0 | 5 | 0 | 0 | 201 | 0 | 2201 | 0 | 16 |
| | 0 | 0 | 0 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pierre | 0 | 0 | 21 | 0 | 0 | 681 | 0 | 7794 | 5 | 72 |
| | 0 | 0 | 39 | 159 | 0 | 1319 | 0 | 15605 | 15 | 169 |
| | 0 | 0 | 27 | 0 | 0 | 950 | 0 | 9167 | 0 | 53 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sak A | 0 | 0 | 13 | 1 | 2 | 452 | 0 | 4946 | 1 | 42 |
| | 0 | 0 | 31 | 24 | 1 | 1120 | 0 | 13127 | 5 | 120 |
| | 0 | 0 | 17 | 229 | 1 | 600 | 0 | 6321 | 11 | 49 |
| | 0 | 0 | 2 | 347 | 41 | 66 | 0 | 719 | 0 | 6 |
| Sak B | 0 | 0 | 4 | 0 | 0 | 163 | 0 | 1731 | 0 | 13 |
| | 0 | 0 | 17 | 26 | 0 | 648 | 0 | 6789 | 5 | 80 |
| | 0 | 0 | 6 | 37 | 0 | 202 | 0 | 2075 | 0 | 23 |
| | 0 | 0 | 0 | 266 | 164 | 0 | 0 | 0 | 0 | 0 |
| Thistle | 0 | 0 | 10 | 120 | 19 | 360 | 0 | 4221 | 2 | 44 |
| | 0 | 0 | 32 | 51 | 0 | 1108 | 0 | 14155 | 0 | 155 |
| | 0 | 0 | 20 | 38 | 0 | 674 | 0 | 7390 | 0 | 66 |
| | 0 | 0 | 0 | 16 | 18 | 0 | 0 | 0 | 0 | 0 |
| Toby | 0 | 0 | 3 | 0 | 0 | 126 | 0 | 1457 | 0 | 9 |
| | 0 | 0 | 21 | 175 | 0 | 771 | 0 | 8919 | 19 | 93 |
| | 0 | 0 | 30 | 0 | 0 | 1118 | 0 | 10975 | 0 | 53 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Two creek | 0 | 0 | 25 | 22 | 3 | 918 | 0 | 9729 | 2 | 98 |
| | 1 | 0 | 26 | 44 | 3 | 969 | 0 | 11912 | 4 | 120 |
| | 0 | 0 | 6 | 31 | 0 | 238 | 0 | 2532 | 3 | 18 |
| | 0 | 0 | 1 | 4 | 4 | 20 | 0 | 224 | 0 | 2 |
| Willow | 0 | 0 | 14 | 107 | 24 | 523 | 0 | 5566 | 3 | 48 |
| | 0 | 0 | 22 | 47 | 14 | 799 | 0 | 9358 | 6 | 88 |
| | 0 | 0 | 10 | 61 | 15 | 360 | 0 | 3781 | 3 | 30 |
| | 0 | 0 | 1 | 42 | 42 | 26 | 0 | 282 | 3 | 2 |

**Table C-7*a***: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean EVIm VPMs for 16 watersheds.

| Onset date | | End date | | Peak date | | Onset value | | End value | |
|---|---|---|---|---|---|---|---|---|---|
| Cassidy | 0 | Cassidy | 0 | Burnt pine | 15 | Cassidy | 22 | Cassidy | 10 |
| Chickadee | 0 | Chickadee | 0 | Cassidy | 19 | Burnt pine | 105 | Millions | 43 |
| Fireweed | 0 | Fireweed | 0 | Mosquito | 21 | Sak B | 115 | Burnt pine | 77 |
| Goose | 0 | Goose | 0 | Sak B | 29 | Millions | 122 | 1A | 85 |
| Kashka | 0 | Kashka | 0 | Two creek | 31 | Two creek | 134 | Mosquito | 90 |
| Millions | 0 | Millions | 0 | Chickadee | 34 | Chickadee | 149 | Two creek | 91 |
| Mosquito | 0 | Mosquito | 0 | Toby | 36 | Mosquito | 161 | Chickadee | 98 |
| Pierre | 0 | Pierre | 0 | Willow | 38 | 1A | 168 | Willow | 127 |
| Sak A | 0 | Sak A | 0 | 1A | 39 | Toby | 170 | Pierre | 164 |
| Sak B | 0 | Sak B | 0 | Sak A | 41 | Willow | 230 | Toby | 169 |
| Thistle | 0 | Thistle | 0 | Millions | 42 | Pierre | 270 | Sak B | 174 |
| Toby | 0 | Toby | 0 | Kashka | 52 | Kashka | 302 | Sak A | 251 |
| Willow | 0 | Willow | 0 | Pierre | 57 | Sak A | 341 | Kashka | 266 |
| Burnt pine | 4 | Burnt pine | 7 | Thistle | 66 | Thistle | 423 | Thistle | 274 |
| Two creek | 6 | 1A | 7 | Fireweed | 69 | Fireweed | 585 | Fireweed | 432 |
| 1A | 7 | Two creek | 8 | Goose | 84 | Goose | 795 | Goose | 656 |

**Table C-7*b***: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean EVIm VPMs for 16 watersheds.

| Peak value | | Length | | Time-int.VI | | Rt of greenup | | Rt of senescence | |
|---|---|---|---|---|---|---|---|---|---|
| Burnt pine | 415 | 1A | 0 | Burnt pine | 3359 | Cassidy | 22 | Burnt pine | 37 |
| Cassidy | 555 | Cassidy | 0 | Cassidy | 4258 | Burnt pine | 53 | Mosquito | 57 |
| Mosquito | 585 | Chickadee | 0 | Mosquito | 4418 | Two creek | 64 | Cassidy | 59 |
| Sak B | 729 | Fireweed | 0 | Sak B | 5547 | Mosquito | 69 | Sak B | 79 |
| Two creek | 780 | Goose | 0 | Two creek | 5906 | 1A | 73 | Two creek | 81 |
| Chickadee | 881 | Kashka | 0 | Chickadee | 6628 | Sak B | 76 | Millions | 88 |
| Toby | 920 | Millions | 0 | Toby | 6896 | Millions | 76 | Chickadee | 88 |
| 1A | 972 | Mosquito | 0 | 1A | 7313 | Toby | 77 | Toby | 98 |
| Sak A | 1006 | Pierre | 0 | Millions | 7612 | Chickadee | 83 | 1A | 98 |
| Willow | 1022 | Sak A | 0 | Sak A | 7662 | Pierre | 88 | Sak A | 103 |
| Millions | 1089 | Sak B | 0 | Willow | 7907 | Willow | 106 | Willow | 104 |
| Kashka | 1198 | Thistle | 0 | Kashka | 8519 | Sak A | 117 | Kashka | 120 |
| Pierre | 1234 | Toby | 0 | Pierre | 9227 | Kashka | 168 | Pierre | 133 |
| Fireweed | 1491 | Willow | 0 | Fireweed | 10394 | Thistle | 180 | Fireweed | 178 |
| Thistle | 1620 | Two creek | 2 | Thistle | 11689 | Fireweed | 191 | Thistle | 179 |
| Goose | 1759 | Burnt pine | 3 | Goose | 12278 | Goose | 249 | Goose | 202 |

**Table C-8*a***: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean NDVIm VPMs for 16 watersheds.

| Onset date | | End date | | Peak date | | Onset value | | End value | |
|---|---|---|---|---|---|---|---|---|---|
| 1A | 0 | 1A | 0 | Mosquito | 4 | Burnt pine | 0 | 1A | 0 |
| Burnt pine | 0 | Burnt pine | 0 | Sak B | 7 | Two creek | 25 | Burnt pine | 0 |
| Cassidy | 0 | Cassidy | 0 | Burnt pine | 10 | 1A | 27 | Cassidy | 0 |
| Chickadee | 0 | Chickadee | 0 | Millions | 10 | Kashka | 28 | Kashka | 0 |
| Fireweed | 0 | Fireweed | 0 | Willow | 11 | Chickadee | 33 | Millions | 0 |
| Goose | 0 | Goose | 0 | Chickadee | 13 | Pierre | 40 | Mosquito | 0 |
| Kashka | 0 | Kashka | 0 | Toby | 13 | Toby | 44 | Pierre | 0 |
| Millions | 0 | Millions | 0 | Two creek | 15 | Thistle | 56 | Toby | 0 |
| Mosquito | 0 | Mosquito | 0 | Goose | 15 | Willow | 64 | Chickadee | 2 |
| Pierre | 0 | Pierre | 0 | Sak A | 16 | Sak B | 82 | Two creek | 3 |
| Sak A | 0 | Sak A | 0 | Thistle | 16 | Mosquito | 89 | Thistle | 9 |
| Sak B | 0 | Sak B | 0 | Fireweed | 16 | Millions | 141 | Sak A | 11 |
| Thistle | 0 | Thistle | 0 | 1A | 17 | Sak A | 150 | Fireweed | 15 |
| Toby | 0 | Toby | 0 | Kashka | 18 | Cassidy | 180 | Willow | 24 |
| Two creek | 0 | Two creek | 0 | Cassidy | 19 | Fireweed | 317 | Sak B | 41 |
| Willow | 0 | Willow | 0 | Pierre | 22 | Goose | 384 | Goose | 48 |

**Table C-8*b***: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean NDVIm VPMs for 16 watersheds.

| Peak value | | Length | | Time-int.VI | | Rt of greenup | | Rt of senescence | |
|---|---|---|---|---|---|---|---|---|---|
| Mosquito | 153 | 1A | 0 | Mosquito | 1702 | Thistle | 1 | Mosquito | 12 |
| Sak B | 253 | Burnt pine | 0 | Sak B | 2649 | Burnt pine | 1 | Sak B | 29 |
| Burnt pine | 385 | Cassidy | 0 | Burnt pine | 4496 | Sak B | 1 | Burnt pine | 30 |
| Willow | 427 | Chickadee | 0 | Willow | 4747 | Two creek | 2 | Millions | 34 |
| Millions | 439 | Fireweed | 0 | Goose | 4912 | 1A | 2 | Toby | 39 |
| Chickadee | 486 | Goose | 0 | Toby | 5338 | Chickadee | 3 | Willow | 42 |
| Goose | 491 | Kashka | 0 | Chickadee | 5440 | Kashka | 4 | Goose | 46 |
| Toby | 504 | Millions | 0 | Fireweed | 5492 | Mosquito | 4 | Chickadee | 48 |
| Thistle | 536 | Mosquito | 0 | Millions | 5611 | Willow | 4 | Fireweed | 50 |
| Two creek | 536 | Pierre | 0 | Two creek | 6099 | Sak A | 4 | Sak A | 54 |
| Fireweed | 552 | Sak A | 0 | Sak A | 6278 | Toby | 5 | Two creek | 60 |
| Sak A | 560 | Sak B | 0 | Thistle | 6442 | Pierre | 5 | 1A | 63 |
| 1A | 611 | Thistle | 0 | 1A | 7024 | Fireweed | 8 | Cassidy | 64 |
| Kashka | 651 | Toby | 0 | Kashka | 7043 | Millions | 11 | Thistle | 66 |
| Pierre | 738 | Two creek | 0 | Pierre | 8141 | Cassidy | 13 | Pierre | 74 |
| Cassidy | 755 | Willow | 0 | Cassidy | 8499 | Goose | 18 | Kashka | 94 |